

**TECTONICS AND SEDIMENTATION
IN THE DEVONIAN AND CARBONIFEROUS
ROCKS OF SW DEVON, ENGLAND**

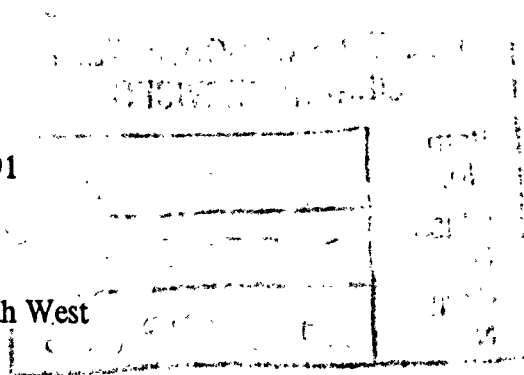
Volume 2

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for National Academic Awards for the degree of Doctor of Philosophy**

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CHAPTER 4

STRUCTURE

4.1 INTRODUCTION

The structures observed in SW Devon are a result of northward migration of the Variscan Deformation Front across SW England (Matthews, 1977; Shackleton *et al.*, 1982; Hobson & Sanderson, 1983). This deformational event gave rise to two tectonic zones of contrasting structural style. They are described here in terms of southern and northern zones (Fig. 4.1).

The chapter is divided into four main sections. Following the introduction, Section 4.2 gives an outline of the structure of the southern zone firstly by describing the small scale structures observed at outcrop, and then by illustrating the large scale structural picture. Section 4.3 presents a description of the small scale structures of the northern zone and their implication for the regional tectonics of the zone. Models are presented for the evolution of the two structural areas described and these are related to the deep structure of SW England. Section 4.4 summarizes the main points of the chapter.

4.2 STRUCTURE OF THE SOUTHERN ZONE

The southern zone encompasses the area between the Start peninsula and Cargreen, 8km north of Plymouth (Fig. 4.1). Detailed mapping of the area around the city of Plymouth and to the south along the South Hams coastline has enabled the construction of a detailed cross section. Similar work to the west around Newquay and to the east around Torbay has allowed additional cross sections through the southern zone to be constructed. Balancing and restoration of these cross sections is attempted but is complicated by the presence of a series of strike slip faults parallel to the lines of section. These faults divide the area into compartments and the structures cannot always be matched across them. It is not possible to limit the structural observations to one compartment for the complete length of the cross section due to the lack of inland exposure. As a result almost all of the work is confined to the coast.

Interpretation of the large scale structure of the southern zone is dependent on small scale structural observations combined with identifying the lithostratigraphy of the region. The small scale structures are described first.

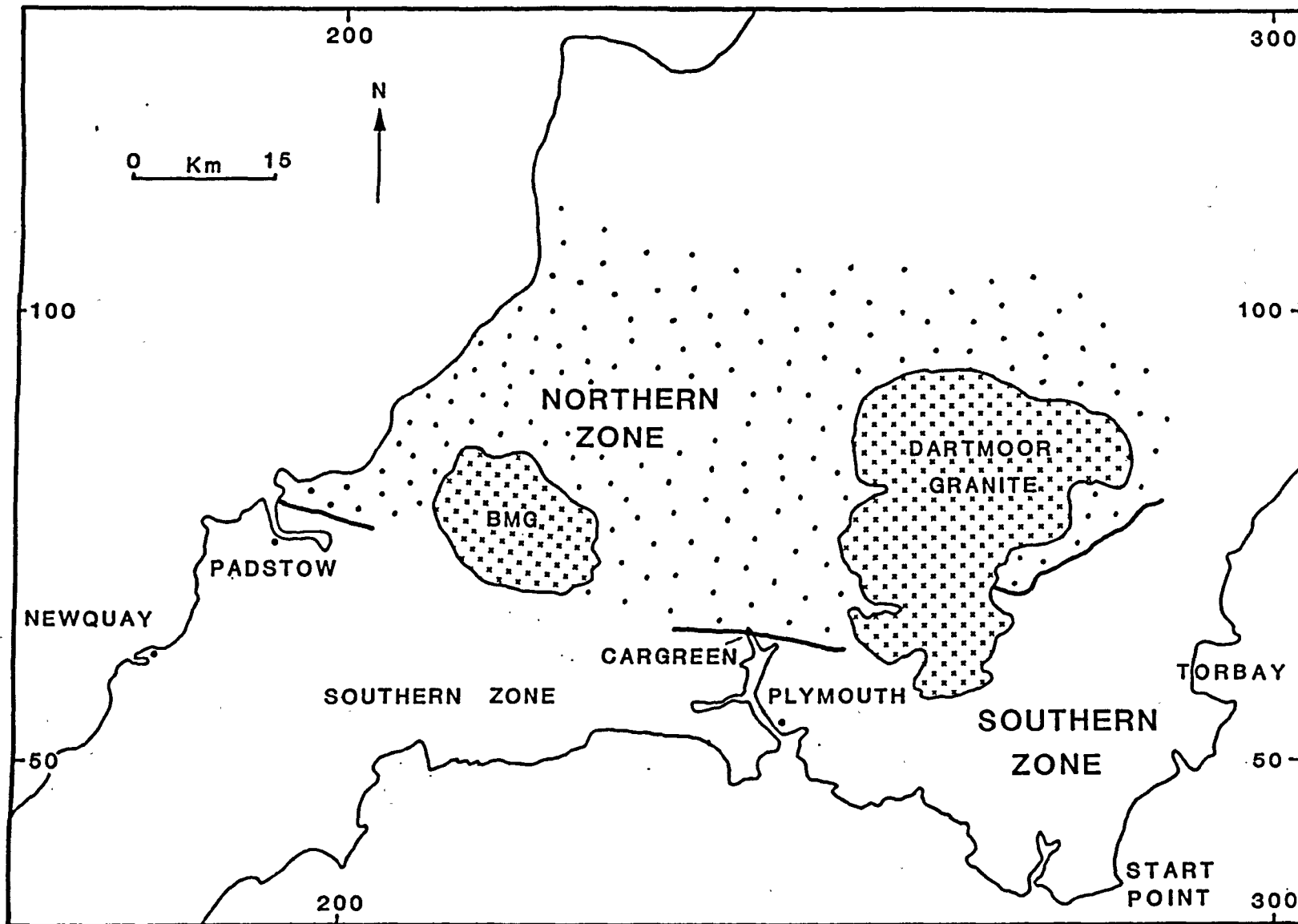


Fig. 4.1 Location map showing the positions of the northern and southern zones which are characterized by different structural styles. BMG - Bodmin Moor Granite.

4.2.1 Small scale structures

Folds

The southern zone is deformed dominantly by folds which formed during the earliest phase of deformation in the area. The folds deform bedding and in general have rounded hinge styles (Pls 4.1 and 4.2). They possess an associated cleavage, which is axial planar or divergent in fine units, and fans in a convergent sense within the competent units (Fig. 4.2). Folds exist on a mesoscopic (outcrop scale) and macroscopic (detected by regional mapping) scale and from data and models presented later appear to form progressively from south to north during the migration of the Variscan Deformation Front.

The style of folding varies throughout the area, however, the folds present in the southern zone are asymmetric, inclined and overturned towards the north. On the whole these folds verge north but locally and on the inverted limbs of some major folds the minor folds verge towards the south (Fig. 4.3). Folding and thrusting on a regional scale produces an allochthonous sequence which is essentially upright, and there is no regional overturning of strata (ie. large scale recumbent fold nappes are absent). Folds are often associated with thrust faults and may originate by growth ahead of thrust tips (tip folds). In this case growth of such folds is governed by propagation of the thrust forwards and upwards through progressively younger strata during ductile bead style deformation (Elliott, 1976; Williams & Chapman, 1983). Examples of this type of fold can be seen in the Bovisand Bay area to the SE of Plymouth.

On the mesoscopic scale the majority of the D1 folds in the southern zone plunge to the SW or NE and on rare occasions they are doubly plunging on an outcrop scale. It is suspected that most folds have this form although they are not commonly recorded as the majority of data is obtained from cliff sections. Fold plunges are gentle and may be regarded as sub-horizontal in attitude on a regional scale (see Figs. 4.4 and 4.5), and essentially non-cylindrical in geometry.

The trend of fold axes varies from north to south along the coast south of Plymouth. In the north they trend ca. NE-SW (Fig. 4.4) whilst as the Start Schist Complex is approached they have a more E-W trend (Fig. 4.5). This is also reflected in the trend of thrusts, bedding and cleavage. The attitude of axial planes is also variable from south to north and combined with younging directions considerably affects fold facing. In the south, just to the north of the Start Schist Complex, the D1 folds are southwards facing (with steep north

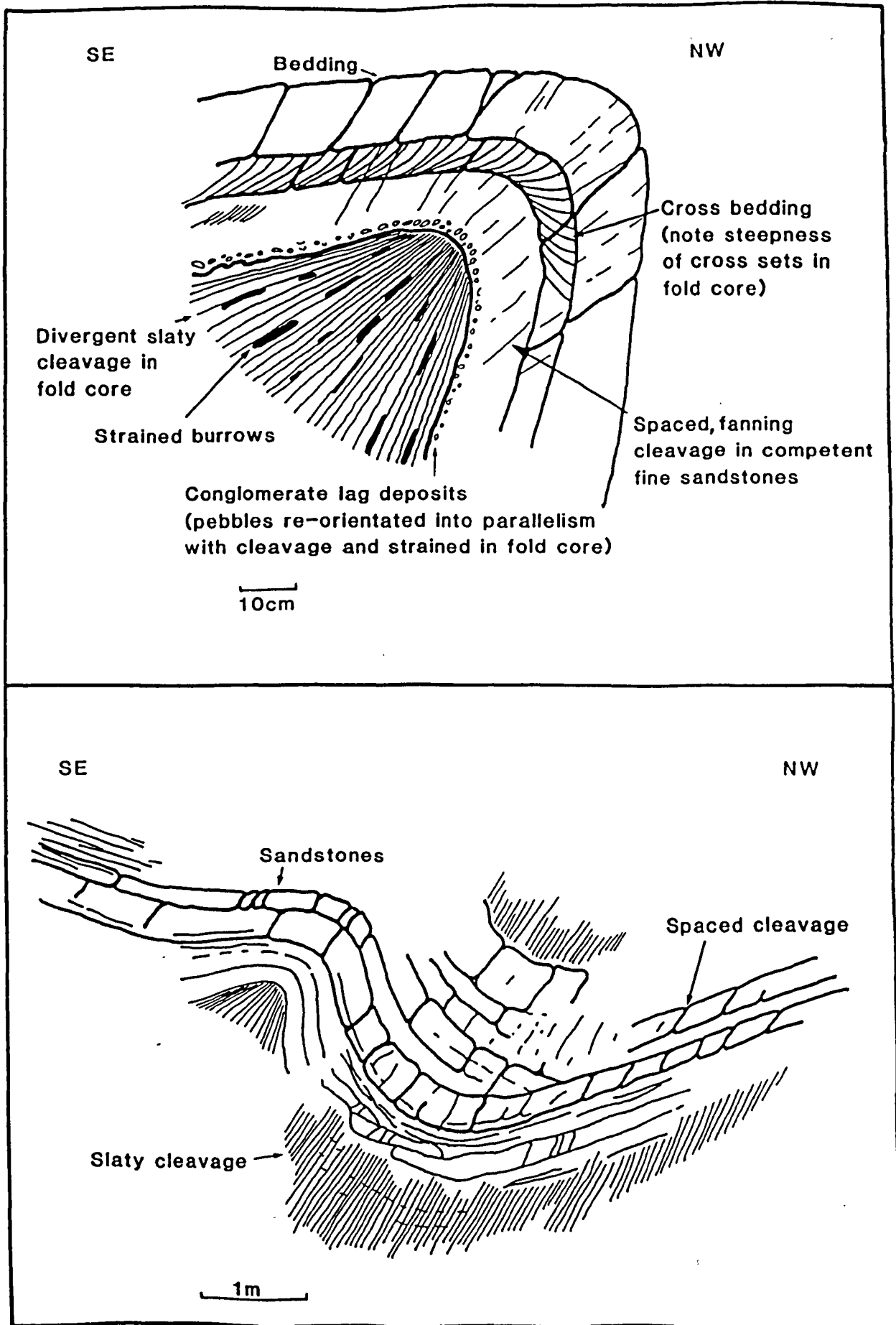


Fig. 4.2 Fold styles in the Lower Devonian rocks to the south of Plymouth; Andurn Point [SX 4915 4960].

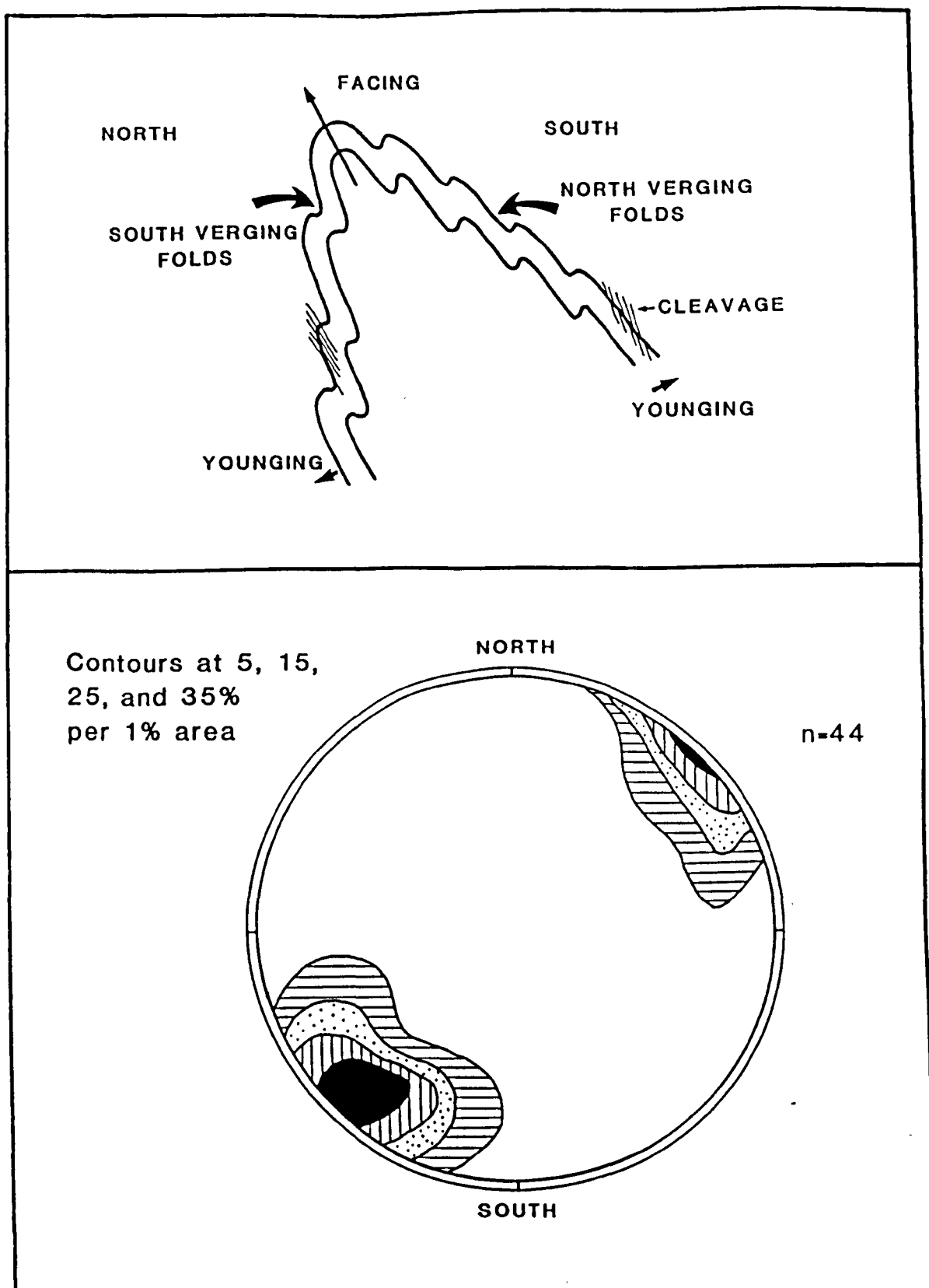


Fig. 4.3 Diagram to illustrate the sense of vergence and facing observed in the rocks of the southern zone.

Fig. 4.4 Contoured stereoplot of first phase fold axes observed in the southern zone.

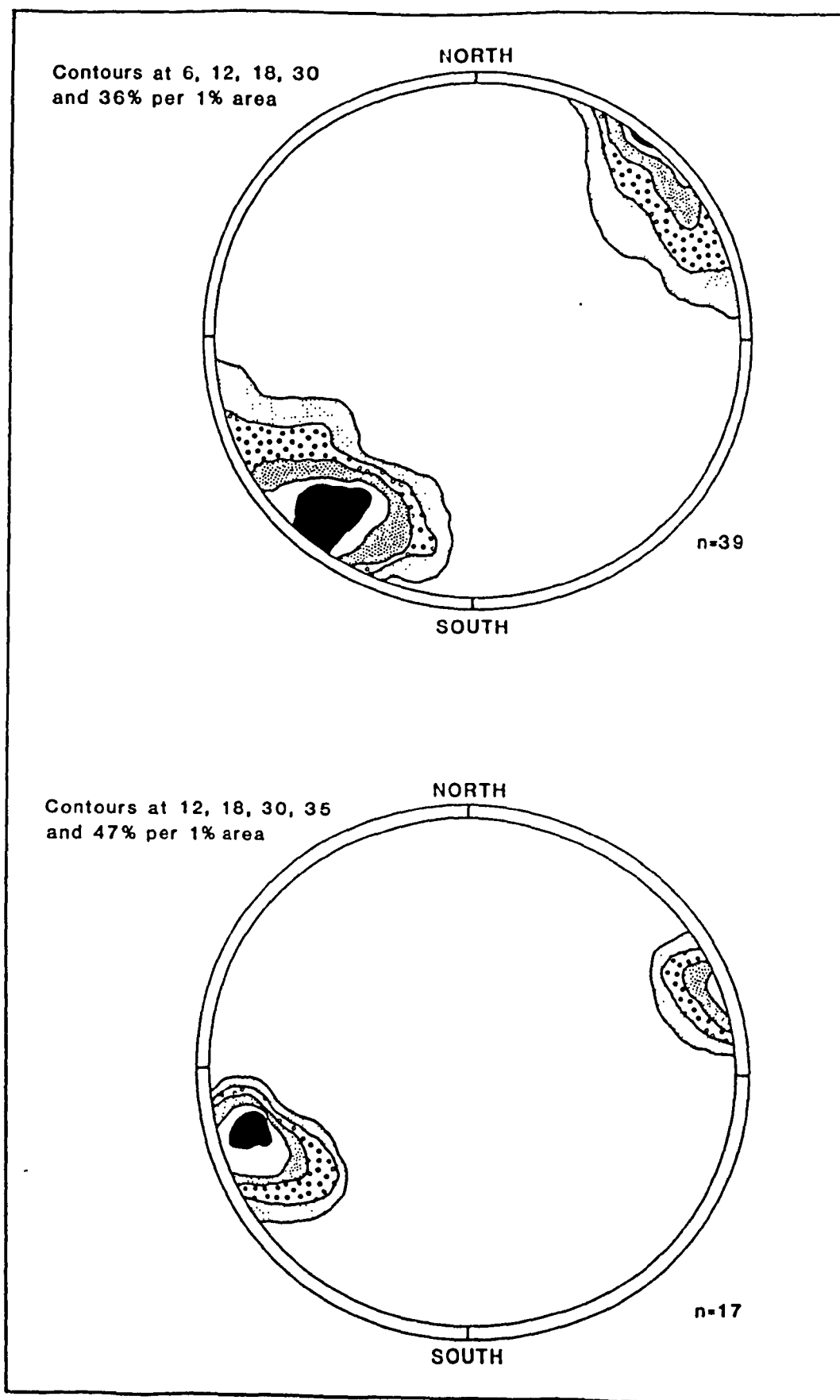


Fig. 4.5 Contoured stereoplots of first phase fold axes observed in the northern part of the southern zone (top). Contoured stereoplots of first phase fold axes observed in the southern part of the southern zone (bottom).



Plate 4.1 First phase fold with axial planar cleavage in the Renney Rocks Formation at Westlake Bay [SX 4925 4920]. The fold is north west verging and upwards facing to the north west. Looking north east.



Plate 4.2 North west verging first phase fold at the base of the Wembury Formation. Cleavage is divergent in the mudstone core and convergent in the more competent sandstone beds; Andurn Point [SX 4920 4975]. Looking south west.

dipping axial planes). A northwards traverse reveals folds that are first upright with vertical axial planes and then further north they face to the NW, firstly along steep southward dipping axial planes and then along moderately dipping axial planes. In the Plymouth region, and to the north, the axial planes are commonly gently southward dipping and facing is to the NW. The above fold geometries are shown in Fig. 4.32.

Thrusts

Thrust faults are common within the Lower Devonian sequence south of Plymouth. They are often very discrete planes (Pl. 4.3), on occasions folded (Pl. 4.4), coated in striated quartz (Pl. 4.5) and sometimes have associated fault breccias (Pl. 4.6). Hanging wall and footwall folding is commonly associated with the thrusts (Pls 4.7, 4.8 and 4.9). Occasionally out-of-sequence thrusts cut through previously folded strata, thus severing fold noses (Pls 4.10 to 4.13) and also cut down section (Fig. 4.6). Out-of-the-syncline thrusts are also present (Pl. 4.14). Second phase crenulation cleavage and folds of slaty cleavage are often found in association with thrust faults (Pl. 4.15 and Fig. 4.7).

Thrusts take the form of the smooth trajectory variety as described by Cooper & Trayner (1986), where they cut through folded strata from one decollement to a higher one via a smooth sigmoidal plane (Fig. 4.8 and Pl. 4.7). Orientation is maintained during the transition from footwall flat to footwall ramp (Cooper and Trayner, 1986). Footwall synclines are invariably associated with the thrusts; an important characteristic of smooth trajectory thrusts (Cooper and Trayner, 1986). This is in contrast to staircase trajectory thrusting more commonly described in the literature (Royse *et al.*, 1975; Elliott, 1977; Butler, 1982), though not necessarily as common in reality.

Thrusts are often folded by the development of structurally lower, later thrusts as deformation proceeds towards the foreland area (see Pl. 4.4). As new thrusts develop the footwall to one thrust becomes the hanging wall to a later, structurally lower, thrust. This also has the effect of refolding bedding and generating crenulation fabrics in the hanging wall of the structurally lower thrust (Fig. 4.9). The hanging wall region to the most recently formed thrust is folded and an axial planar crenulation fabric may develop. These second phase folds are co-axial to the earlier formed structures and are associated with the same deformation event (Fig. 4.10). Similar features have been described by Sanderson (1982) in hanging wall blocks as they pass over thrust ramps. Second phase structures are not found adjacent to all thrusts but are commonly observed in sequences of cleaved pelites (Pl. 4.15).

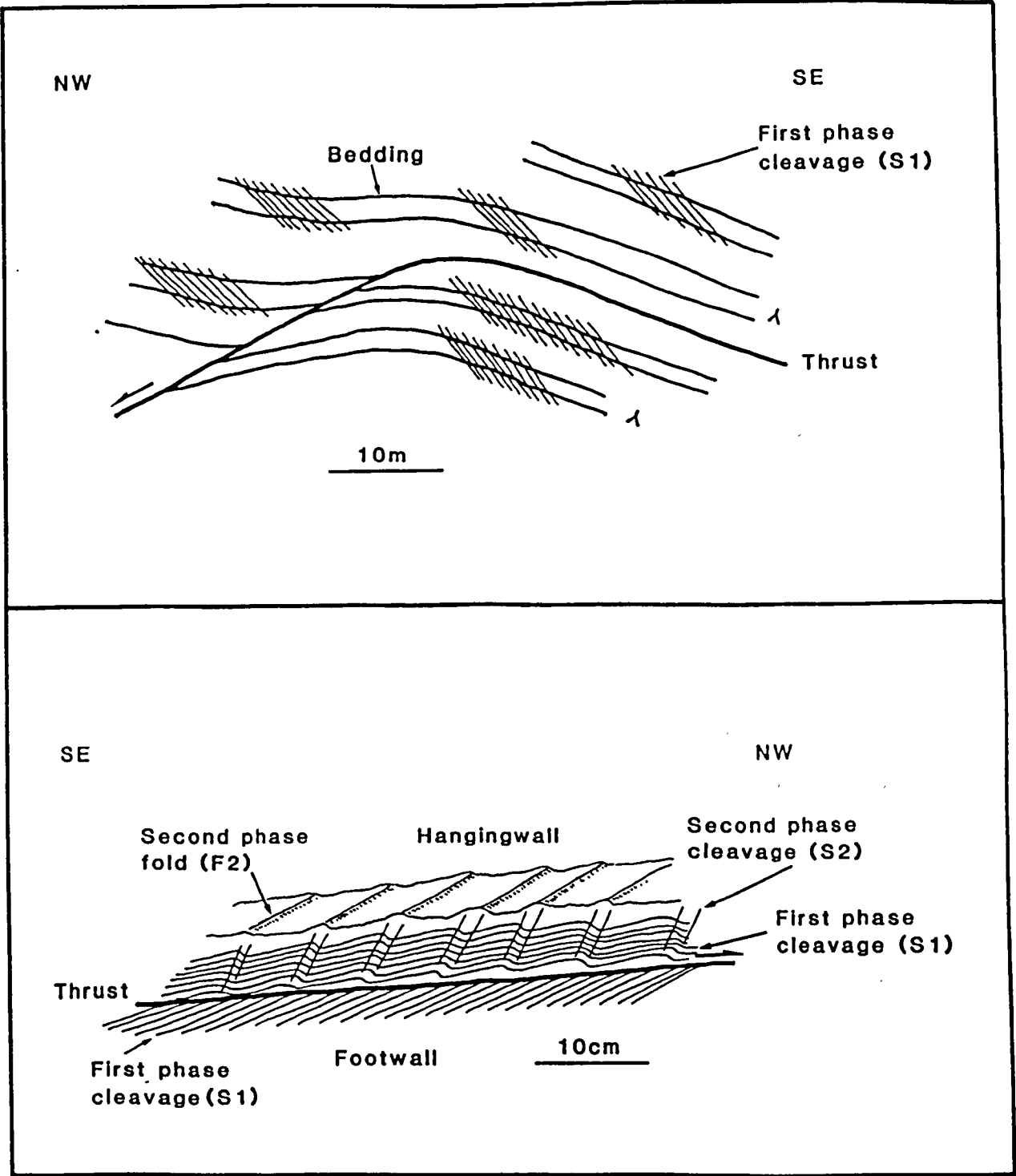


Fig. 4.6 Out-of-sequence thrust in the Dartmouth Group rocks east of Wembury Beach [SX 5300 4785].

Fig. 4.7 Thrust related second phase cleavage in the Dartmouth Group rocks south of Dartmouth [SX 8880 4955].

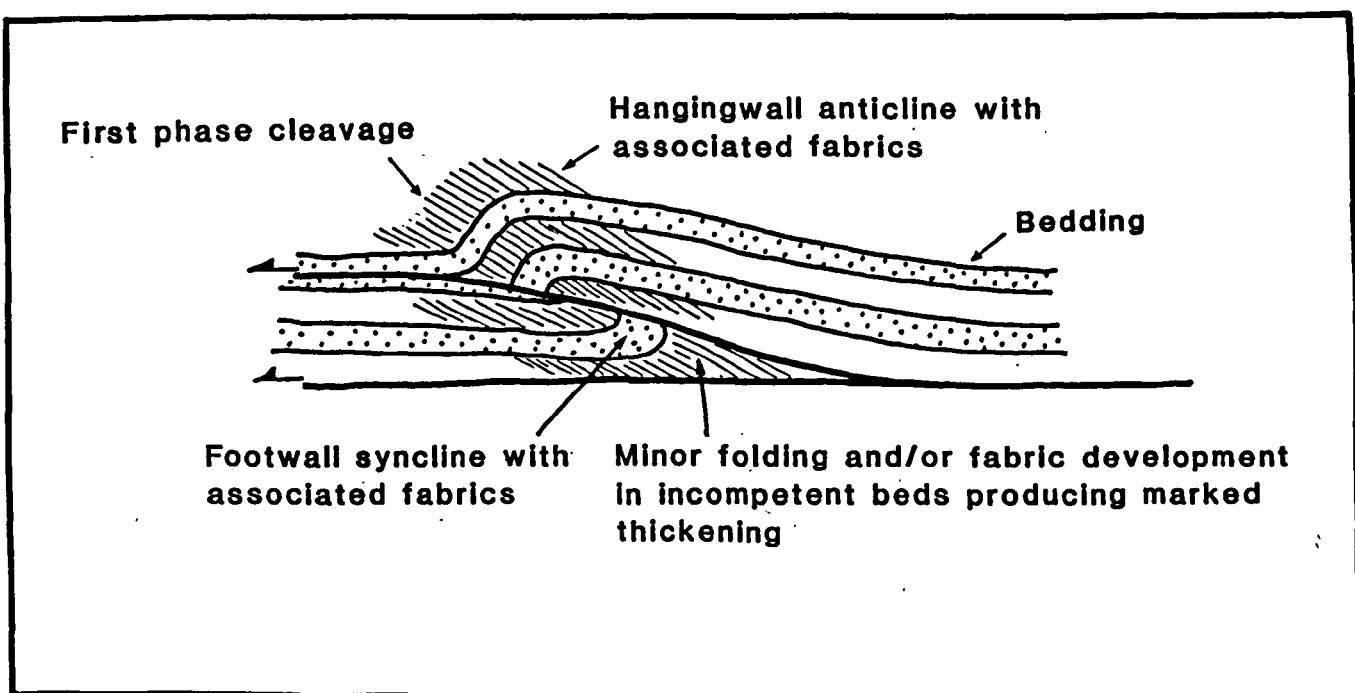


Fig. 4.8 Smooth trajectory thrust and associated hangingwall and footwall structures and fabrics (after Cooper and Trayner, 1986).

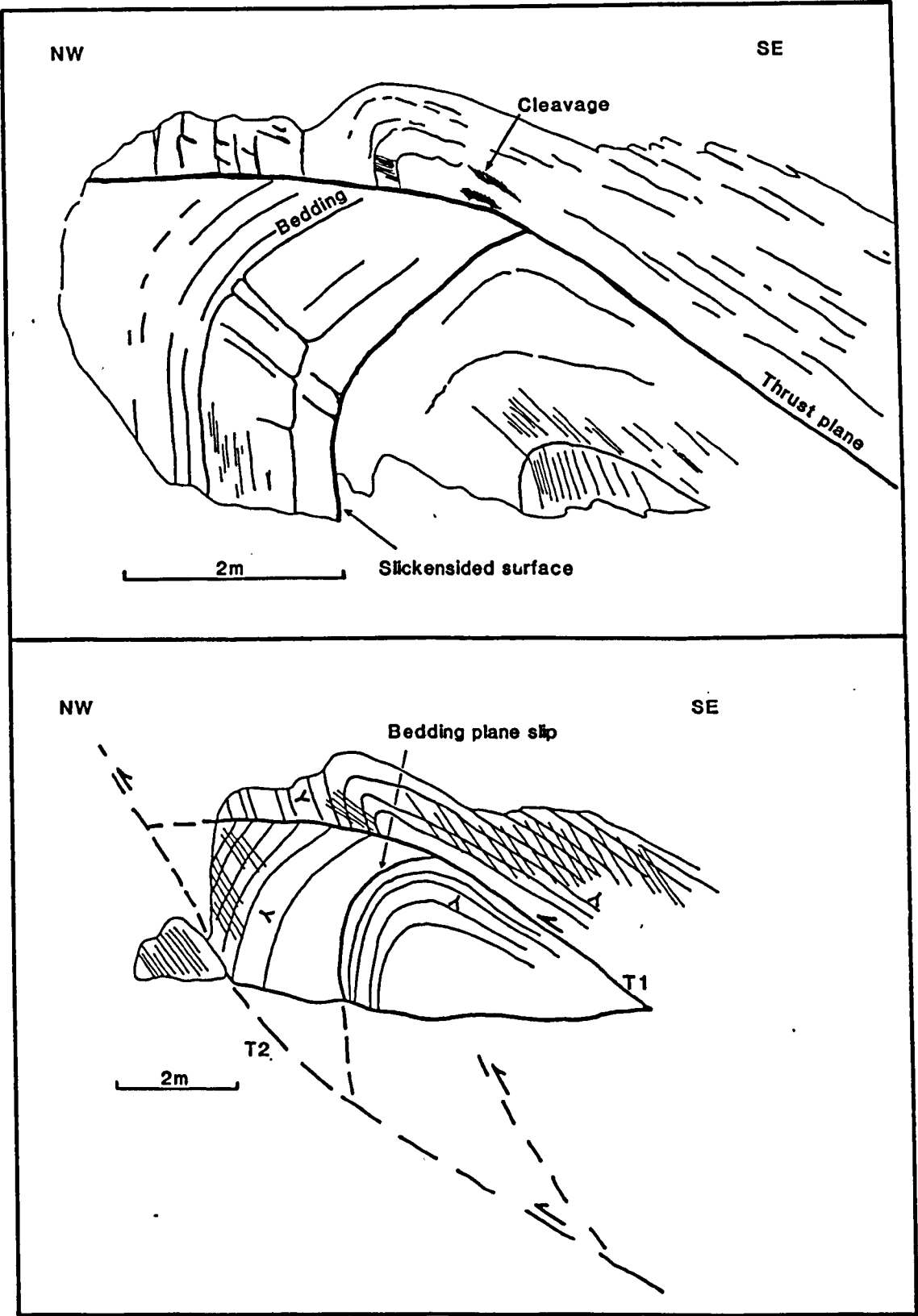


Fig. 4.9 Line drawing of a refolded fold produced by progressive thrust development towards the foreland (compare with Pl. 4.4); Renney Rocks [SX 4925 4875].

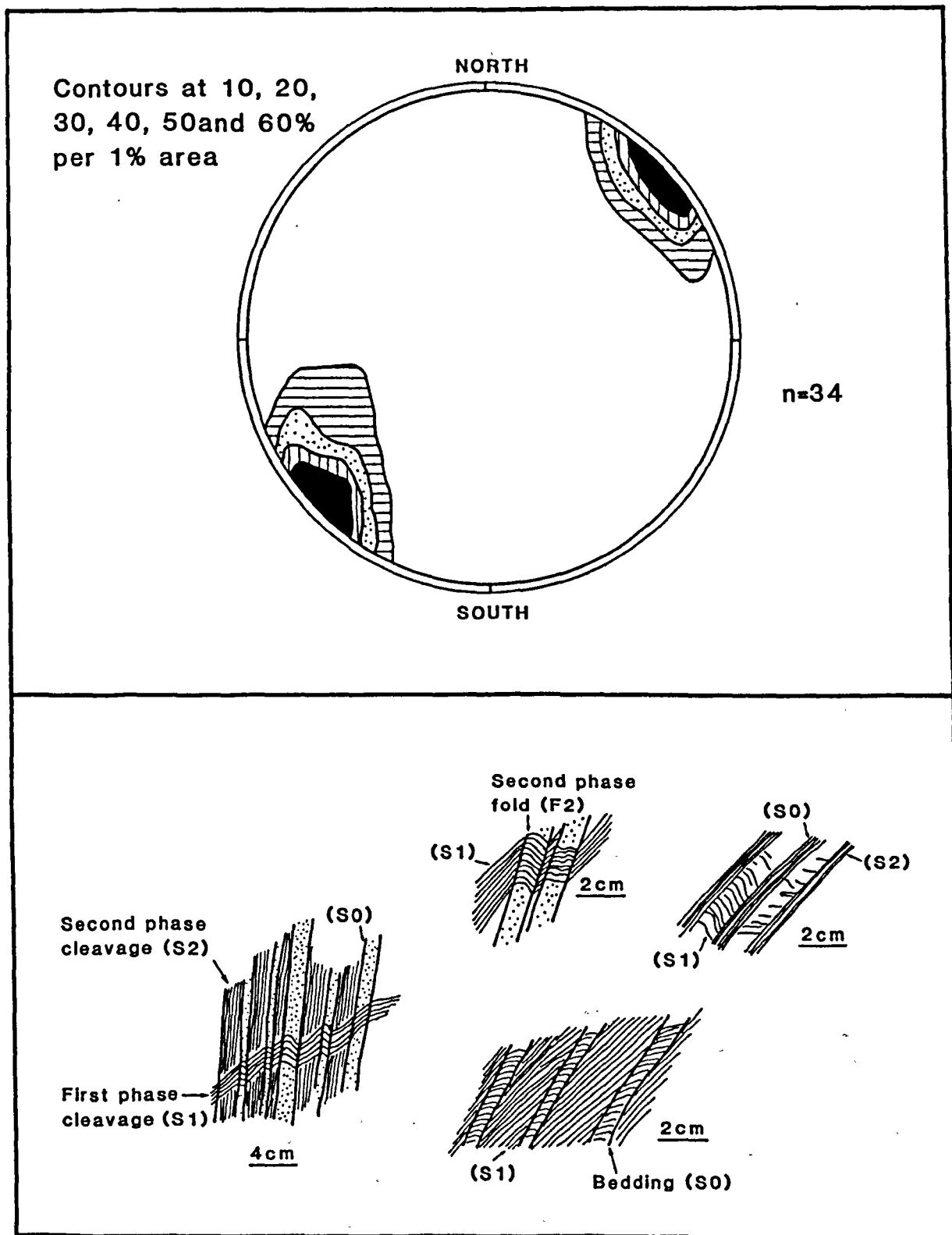


Fig. 4.10 Contoured stereoplot of the second phase fold axes observed in the southern zone.

Fig. 4.11 Bedding and cleavage relations in the Dartmouth Group rocks to the south of Dartmouth [SX 8860 5020]. Note that second phase fold axes occur at lithological interfaces and may correspond to modified cleavage refraction.



Plate 4.3 Planar thrust fault in the Renney Rocks Formation between Heybrook Bay [SX 4965 4870] and Renney Rocks [SX 4925 4875]. Looking south west. Rucksack for scale.



Plate 4.4 Refolded fold/thrust structure at Renney Rocks [SX 4925 4875]. Looking north east. Compare with Fig. 4.9.

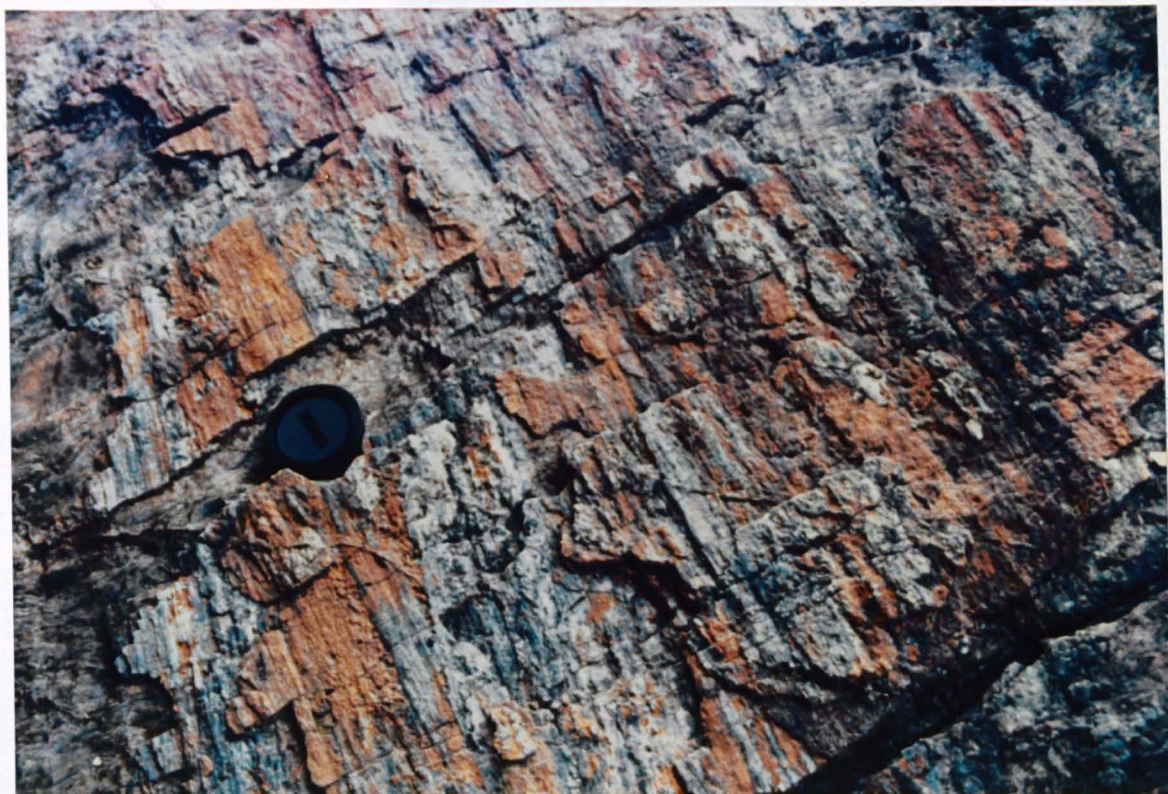


Plate 4.5 Striated quartz on thrust plane used to determine slip directions. Looking north west.



Plate 4.6 Thrust fault and associated fault breccia within the Wembury Formation; Wembury Bay [SX 5170 4840]. Looking north west.



Plate 4.7 Fold/thrust structure in the Staddon Grit Formation at Crownhill Bay [SX 4925 4980]. Looking north east.



Plate 4.8 Fold/thrust structure in the Warren Formation at Gara Point [SX 5240 4690]. Looking north east.



Plate 4.9 Close up of Pl. 4.8.



Plate 4.10 Fold/thrust structure in the Wembury Formation at Wembury Bay [SX 5170 4840]. Note out-of-sequence nature of fault where it cuts pre-folded strata in its footwall. Looking south west. Camera for scale.



Plate 4.11 Close up of 4.10.



Plate 4.12 Close up of 4.11. The duplex has possibly formed by re-activation of primary sedimentary lateral accretion surfaces. Restoration is also hindered by it cutting pre-folded strata.



Plate 4.13 Close up of Pl. 4.10 showing the thrust cutting up and down section, a function of its out-of-sequence nature.



Plate 4.14 Out-of-the-syncline thrust in the sandstones at the base of the Wembury Formation; Andurn Point [SX 4920 4975]. Looking south west. Compare with Fig. 4.2.



Plate 4.15 Second phase folds which fold a pre-existing first phase penetrative cleavage in the Bovisand Formation. Folds have sub-vertical axial planes and an associated steep second phase crenulation cleavage; Crownhill Bay [SX 4925 4980]. Looking north east.



Plate 4.16 Interbedded sandstone and mudstone at the top of the Bovisand Formation. Sandstones display spaced cleavage whilst the mudrocks display a penetrative fabric. Cleavage refraction occurs at the sandstone/mudrock interfaces; Crownhill Bay [SX 4925 4980]. Looking north east.

Development of the first phase cleavage

Two types of first phase cleavage are present in the Devonian rocks of the study area. Their form is dependent on the host lithology. The coarser, more competent lithologies display a spaced cleavage (cf. Powell, 1979) (Pls 4.16 and 4.17) whilst the finer, less competent lithologies display a pervasive foliation (Pls 4.18, 4.19 and 4.20). The spaced cleavage of the sandstones is a tectonic striping which fans convergently around the first phase mesoscopic folds. The spaced fabric remains steeper than bedding on upright fold limbs but is less steep than bedding on overturned fold limbs. The spacing of the cleavage planes varies between 0.5cm and 20cm and they sometimes join and rejoin in an anastomosing fashion. The cleavage planes in the siltstones tend to be more closely spaced, however, in the claystones the fabric totally re-orientates the clastic grains resulting in a pervasive foliation (slaty cleavage) (Pl. 4.19). This rock type is distinctly anisotropic. The slaty cleavage is regarded as being axial planar to the early mesoscopic folds although divergent cleavage fans are present in some fold hinge regions. It is because of this relationship that the slaty cleavage is often near parallel to bedding on fold limbs. The intersection of the first phase cleavages with bedding produces a lineation parallel or sub-parallel to the first phase fold axes.

The zones between spaced cleavage planes have a high ratio of quartz to phyllosilicates (muscovite, chlorite, sericite and altered clays). These areas may be referred to as quartz lithons or Q domains (Pl. 4.21). The quartz grains within this domain are invariably in contact with each other and show sutured contacts (Pl. 4.22). Cementation by dissolved silica resulting from this indicates that pressure solution has occurred. The cleavage planes, which appear as multiples of thin fractures at outcrop, are dominated by phyllosilicates. They are referred to as P domains (cf. Williams, 1972) and the grains (including quartz) present within them have a high degree of preferred orientation, resulting from physical rotation during deformation (Pl. 4.19). Quartz grains are truncated on the margins of the P domains indicating corrosion during fluid migration along the P domain. The quartz grains present in the P domains are often altered and replaced and are sometimes wrapped by micas. Bedding plane surfaces are sometimes uneven and have a serrated appearance. This is attributed to the deposition of silica at the end of cleavage planes. The process of formation seems to have been enhanced by volume decrease resulting from the migration of silica along the P domains. Hence it seems reasonable to assume that the development of the P domains, and also the cleavage itself, is due to the selective removal of quartz during pressure solution.

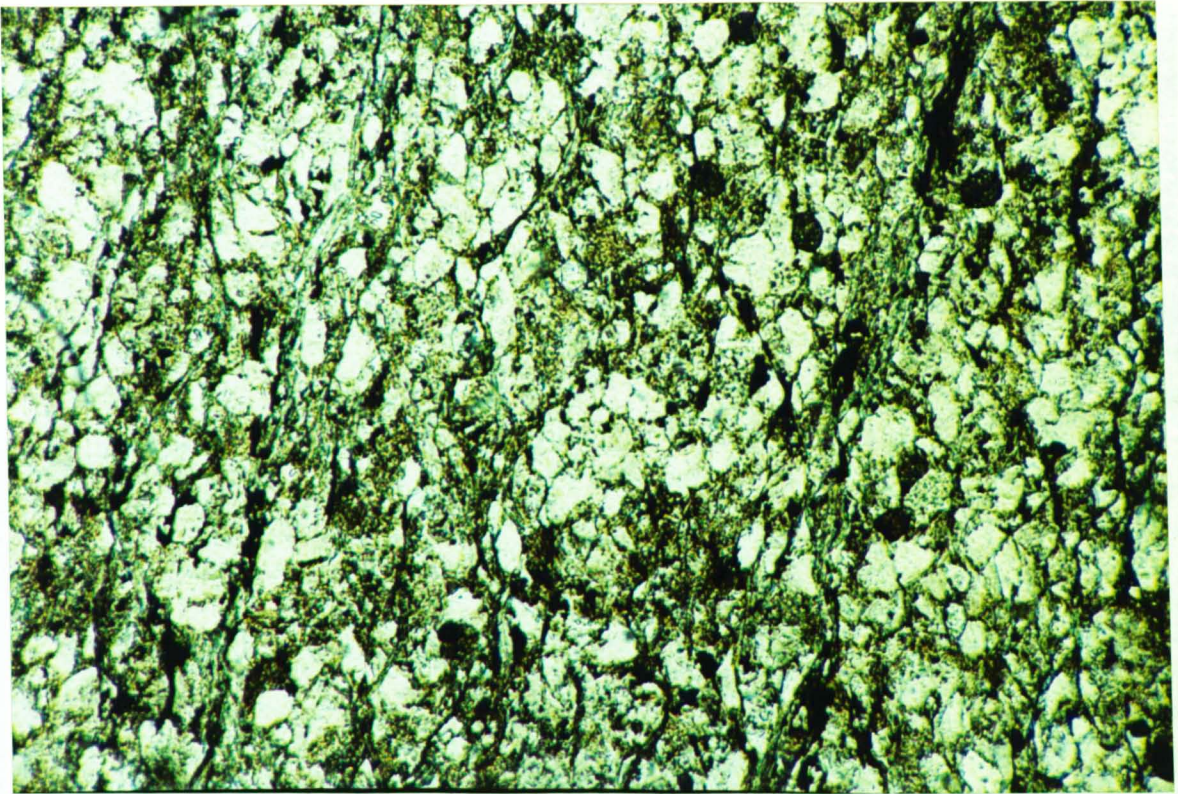


Plate 4.17 Photomicrograph (x64) of the spaced cleavage observed in competent units of the Renney Rocks Formation, plane polarised light. Heybrook Bay [SX 4965 4870].

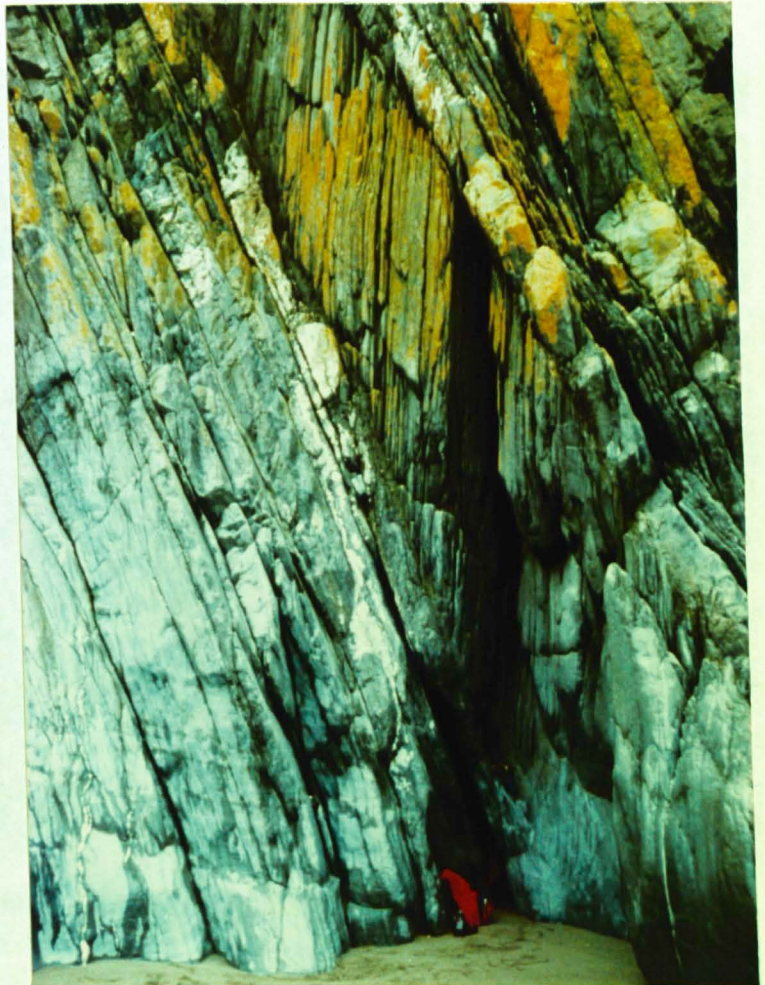


Plate 4.18 Pervasive, first phase cleavage (sub-vertical) in the mudrocks of the Warren Formation, Stoke Beach [SX 5650 4640]. Looking north east. Bedding dips steeply to SE (right).

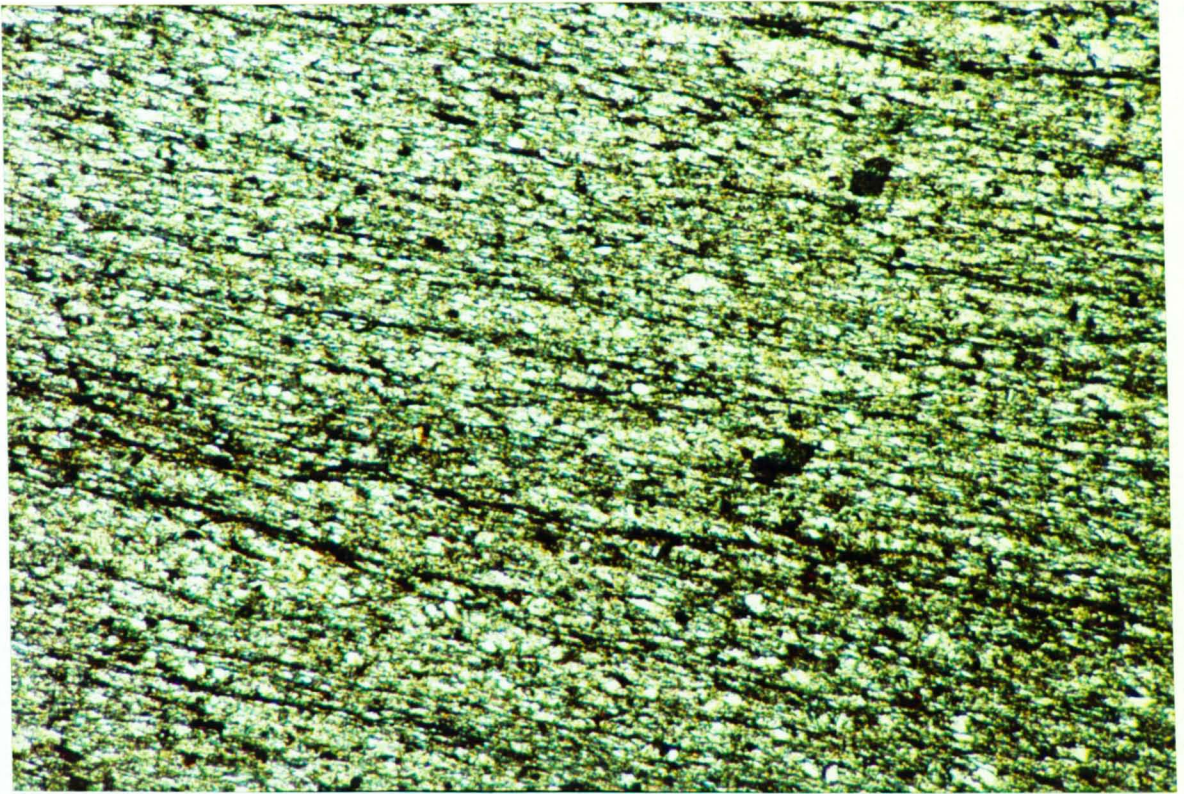


Plate 4.19 Photomicrograph (x64) of silty claystones in the Renney Rocks Formation showing the nature of the pervasive first phase fabric; plane polarised light. Heybrook Bay, [SX 4965 4870].

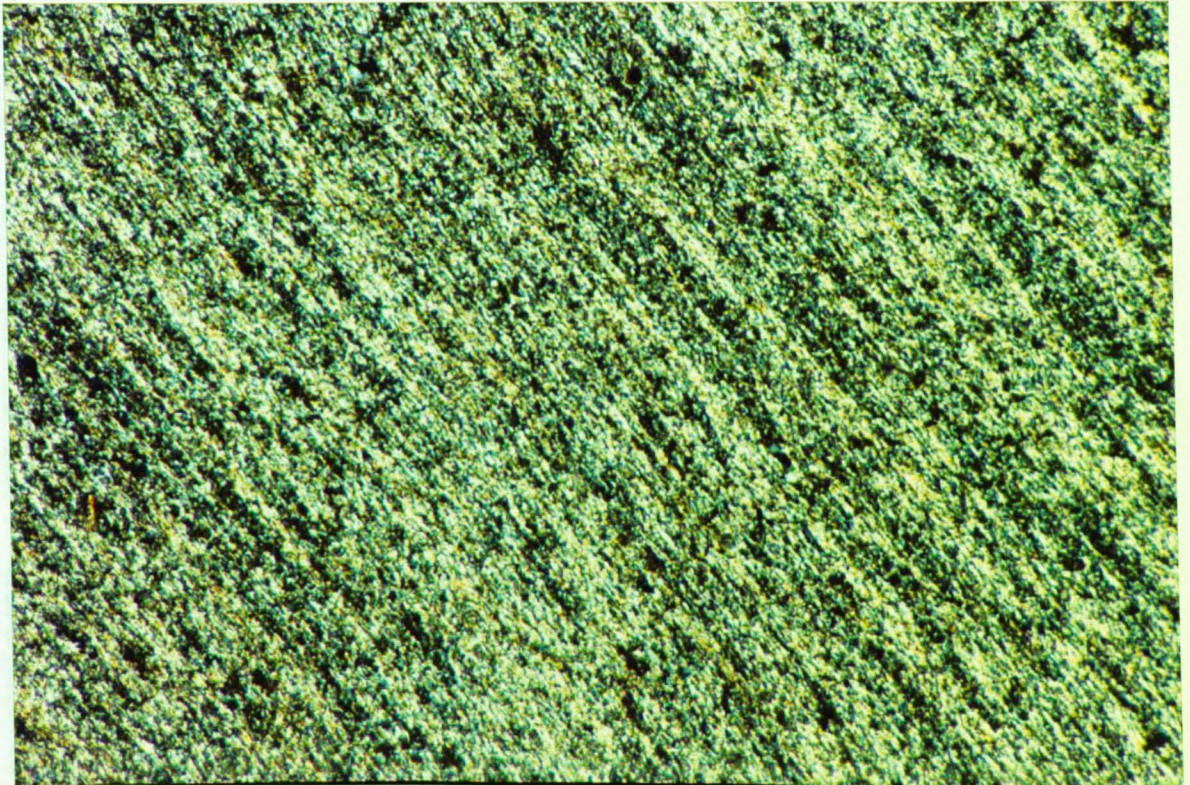


Plate 4.20 Photomicrograph (x64) of the Upper Devonian/Lower Carboniferous Slates showing the pervasive first phase cleavage; crossed polars. Hole's Hole [SX 4320 6520].

Plate 4.21 Photomicrograph (x64) of the quartz (right) and phyllosilicate (left) domains produced during the formation of the first phase cleavage; plane polarised light. Renney Rocks Formation, Heybrook Bay [SX 4965 4870].

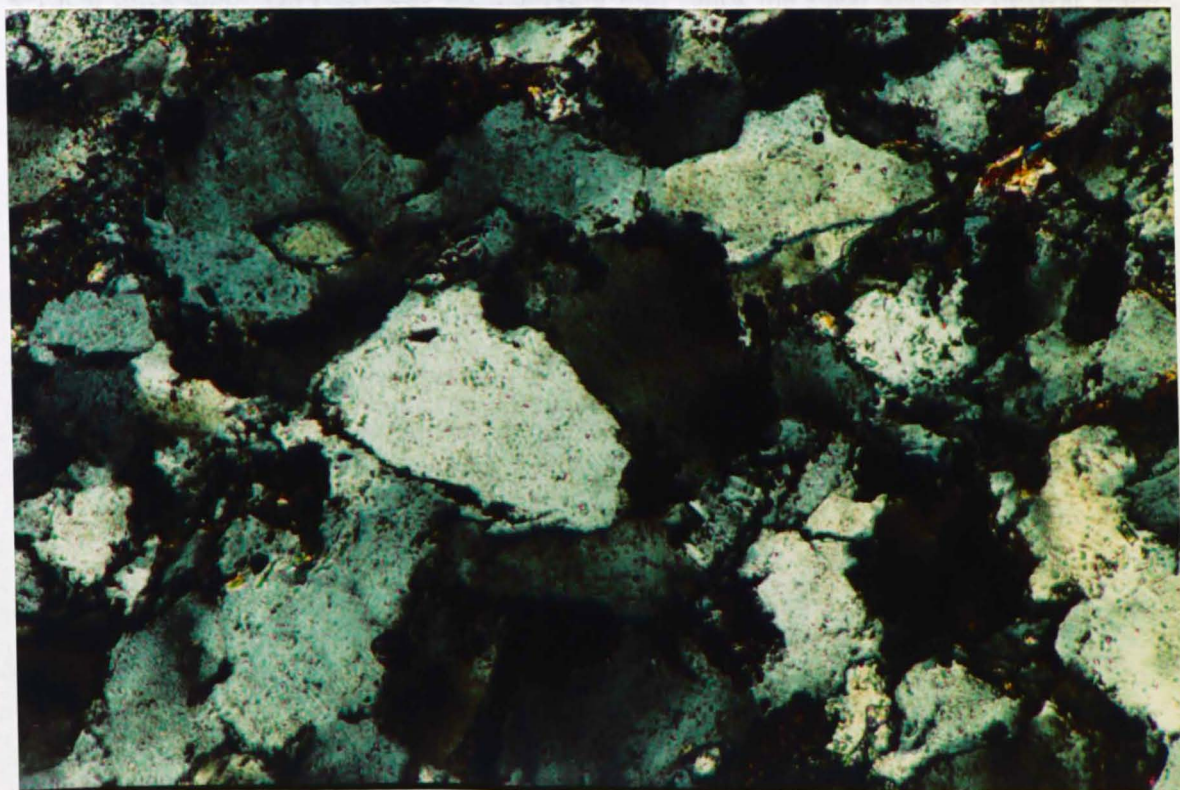


Plate 4.22 Photomicrograph (x160) of sutured contacts between quartz grains in the Staddon Grit Formation; crossed polars. Jennycliff Bay [SX 4900 5170].

The slaty cleavage is a planar fabric that is uniformly developed and penetrates the whole rock. This cleavage forms perpendicular to the direction of maximum finite shortening (after Sharpe, 1847; see also Sorby, 1856) and its presence indicates that the compressive strain exceeds 30% (Cloos, 1947; see also Dietrich & Carter, 1969; Williams, 1976). In the low grade metamorphic rocks of the area the slaty cleavage has been formed by the mechanical reorientation of the grains and by the growth of the phyllosilicates.

Where adjacent beds of differing lithology occur the cross-cutting cleavage refracts at the interface between the two lithologies (see Pl. 4.16). The cleavage attains a lower angle to bedding in the finer unit. The thinner the clay unit the greater the angular difference between the two units will be. However, in the case of a graded bed, coarse grained at its base and fine grained at its top, individual cleavage planes curve and display an upwards decrease in the cleavage/bedding angle. This cleavage refraction is used to discern the way up of strata when sedimentary structures are rare or not obvious at outcrop. However, in some cases cleavage refraction is recorded at both the top and bottom of siltstone units and is not a function of lithological grading. In this case the cleavage displays a sigmoidal geometry in a profile plane (Pl. 4.23) and the fold axes defined by the curving cleavage trend approximately NE-SW (032°) and have little or no plunge. These structures are observed in 4-15cm thick units. On right way up, flat-lying fold limbs the shear sense is dextral when viewed to the west. It is inferred that this sigmoidal cleavage is produced by shearing in a direction towards 302° (the approximate trend of the regional transport direction) and may be directly related to flexural slip folding (see also Trayner and Cooper, 1984).

Development of the second phase cleavage

This fabric is local in occurrence throughout the area and is invariably confined to the pelitic rocks. It deforms the pre-existing slaty cleavage resulting in the formation of F2 folds and a crenulation cleavage (Cosgrove, 1976) (Pls 4.24 and 4.25). The crenulation cleavage planes are closely spaced and in some instances become pervasive varying with respect to the proportion of silt size grains present. The greater the silt content the more widely spaced the cleavage planes. In outcrop the planes appear to be spaced at intervals of around 0.5 to 1cm, however, in thin section the spacing is noticeably less. Q and P domains are also produced during crenulation cleavage formation. In the P domains the first phase fabric becomes partially transposed, merging with the second phase fabric which in turn forms the margins to the domains. The first phase fabric traverses the second phase Q



Plate 4.23 Cleavage geometry in the slates of the Wembury Formation at Andurn Point [SX 4920 4975]. Note sygmoidal form is a function of flexural slip and not sedimentary grading. Looking south.



Plate 4.24 Sub-vertical crenulation cleavage in the Bovisand Formation, Crownhill Bay [SX 4925 5025]. First phase fabric dips moderately to the south east. Looking north east. Penny for scale.

Plate 4.25 Photomicrograph (x64) of the crenulation cleavage, plane polarised light. Bovisand Formation, Crownhill Bay [SX 4925 5025].

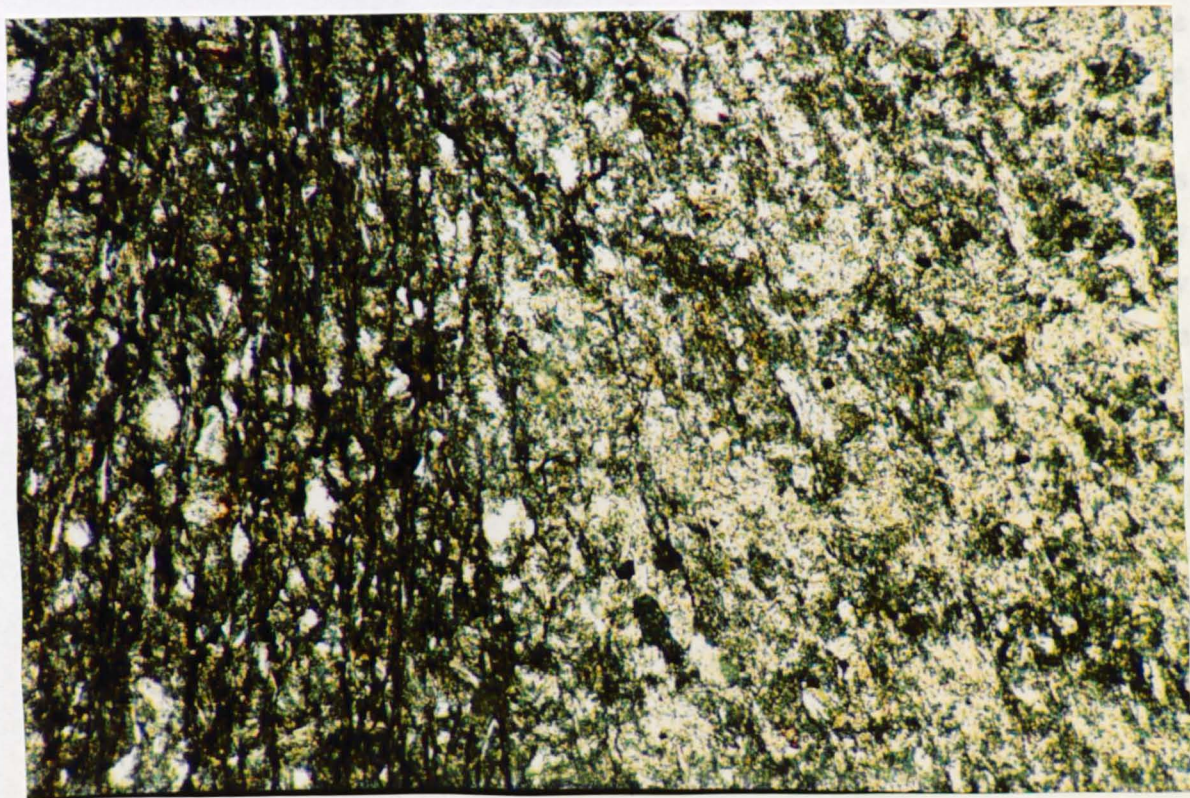


Plate 4.26 Photomicrograph (x64) of the second phase P (left) and Q (right) domains. Note that the first phase fabric traverses the Q domain; plane polarised light. Bovisand Formation, Bigbury Bay [SX 6740 4100].

domains (Fig. 4.11 and Pl. 4.26). The second phase P domains are major pathways for the migration of silica during pressure solution. Q/P domain margins form axes to small-scale second phase folds. The silica removed during pressure solution is re-deposited in vein systems (Pls 4.27, 4.28 and 4.29).

The crenulation cleavage does not penetrate the rock on all scales like the pervasive slaty cleavage. However, it does form discrete planar discontinuities which give rise to local structural weaknesses in the rock. Crenulation cleavage forms by microbuckling with or without pressure solution and re-distribution of the minerals (Cosgrove, 1976). Buckling of a pre-existing mineral fabric (slaty cleavage) leads to the development of new cleavage planes in the axes of the micro-buckles. The initial fabric would be one in which most platy minerals are oriented perpendicular to the subsequent axes of the crenulations. As the micro-folds tighten the minerals on the limbs re-align so that they lie on a plane, producing a plane of weakness. These occur at regular intervals and comprise the crenulation fabric, a result of mechanical rotation of mineral grains during folding.

The secondary fabric is axial planar to small scale folds which are generally co-axial to the primary folds. Second phase fold axes sometimes occur at bedding interfaces (see Fig. 4.11). In this case development of the second phase cleavage may be due to transposition of the pre-existing first phase cleavage and may correspond to modified cleavage refraction. The intersection lineation of the first phase cleavage and the crenulation fabric is parallel to the local second phase fold axes (Pl. 4.30).

Second phase cleavage zones appear to be directly related to thrust faults and is present at various scales. On a minor scale the development of the crenulation fabric is mainly observed in the hanging wall regions of sub-horizontal thrust faults but dies out upwards away from the fault over a distance of centimetres (Fig. 4.7). It is therefore assumed to be generated during growth of the thrust. On a larger scale, eg. at Bovisand, second phase cleavage zones may extend for distances of up to 100m in the coastal outcrop. In this particular case numerous thrusts disrupt the sequence and are thought to be directly associated with the zone of secondary cleavage. The development of secondary cleavage in such a case may be a function of successive thrust movements where structurally lower, 'later' thrusts fold a pre-existing structurally higher thrust plane and any other rock fabric within the hanging wall (eg. bedding or slaty cleavage) (Fig. 4.12 and Pl. 4.4). The folding of an earlier cleavage will result in the formation of a crenulation fabric with the resulting folds being coaxial to the earlier formed folds. At Bovisand the second phase folds, and associated second phase cleavage, occur in the core of a macroscopic, secondary fold which is in turn

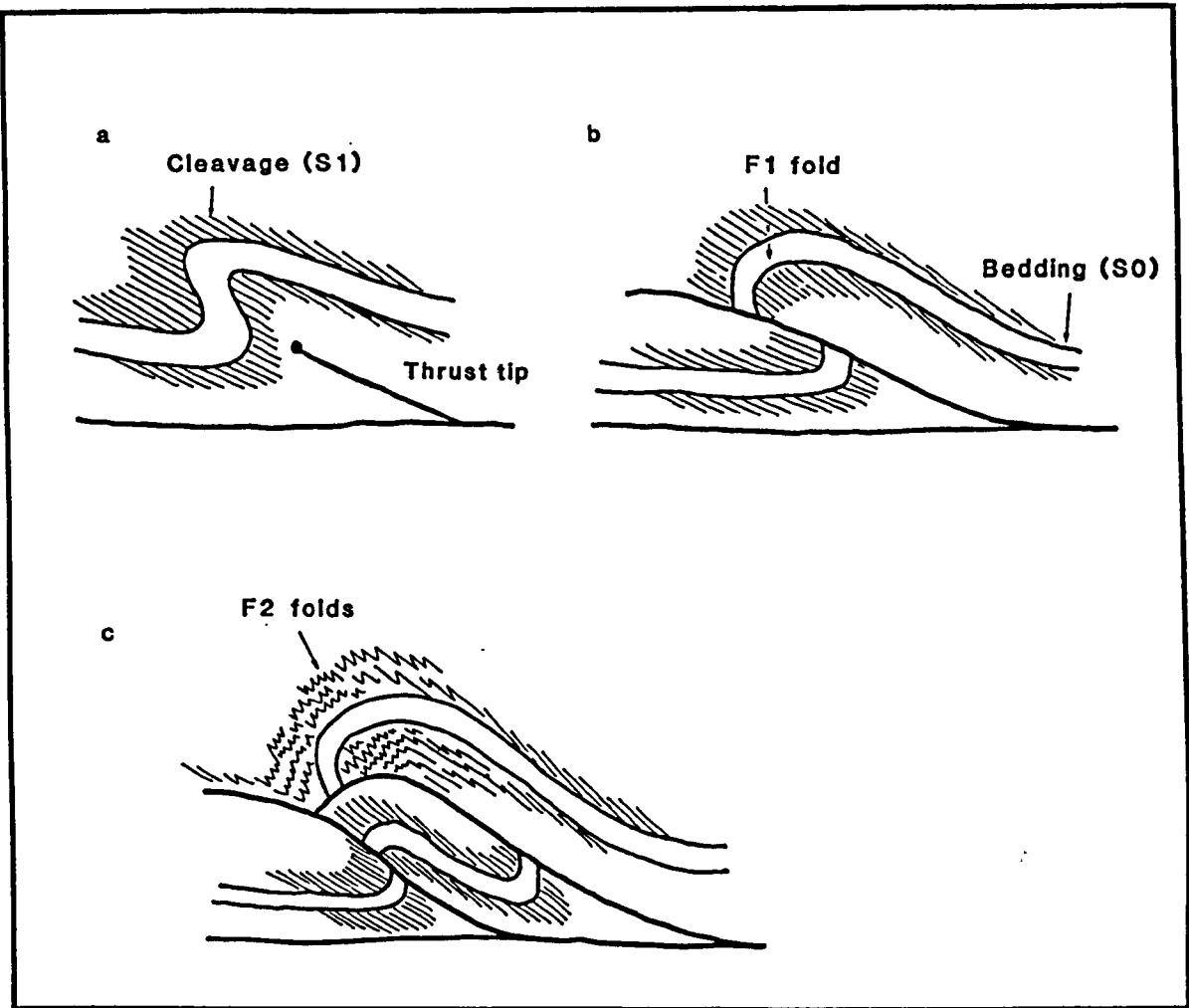


Fig. 4.12 Diagram to show how progressive thrust development may lead to refolding of pre-existing fabrics.



Plate 4.27 Quartz vein array indicating dextral shear within the Renney Rocks Formation between Andurn Point [SX 4920 4975] and Westlake Bay [SX 4925 4920]. Looking north east.

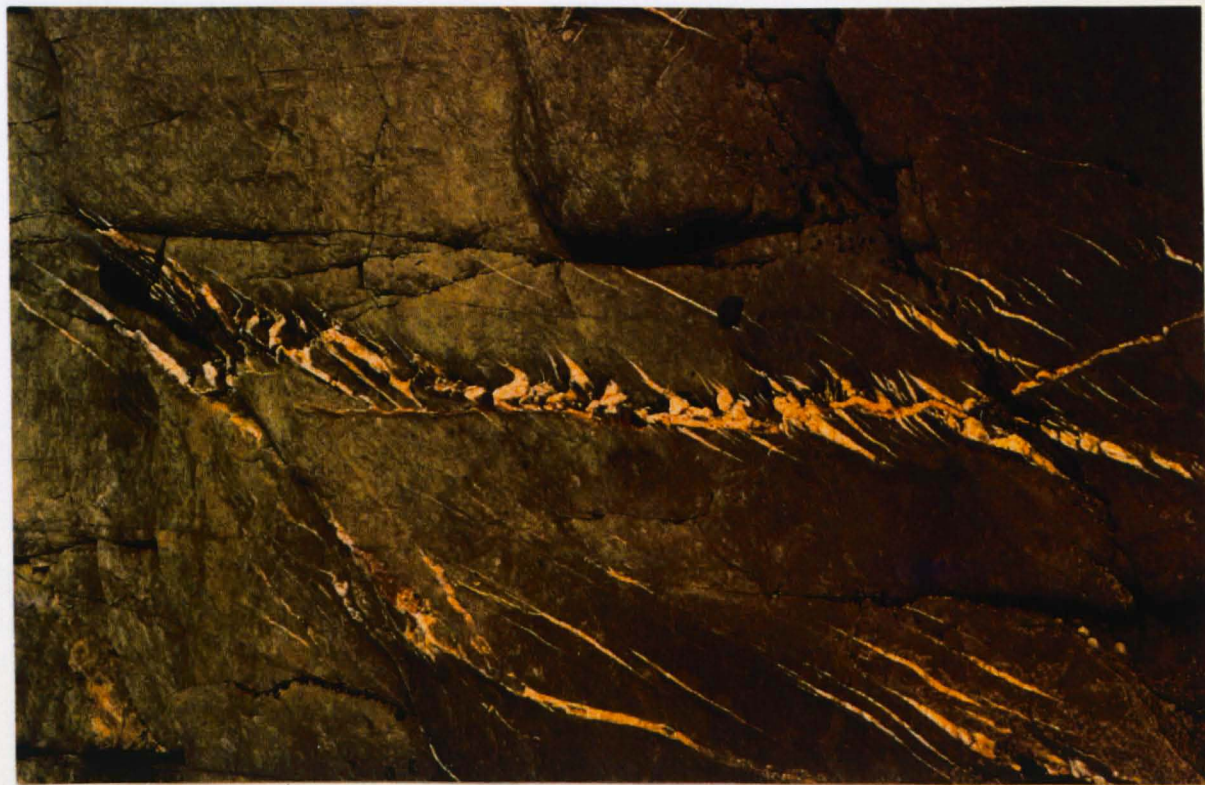


Plate 4.28 Quartz vein array indicating dextral shear within the Yealm Formation; Wadham Rocks [SX 5800 4700]. Looking north east.

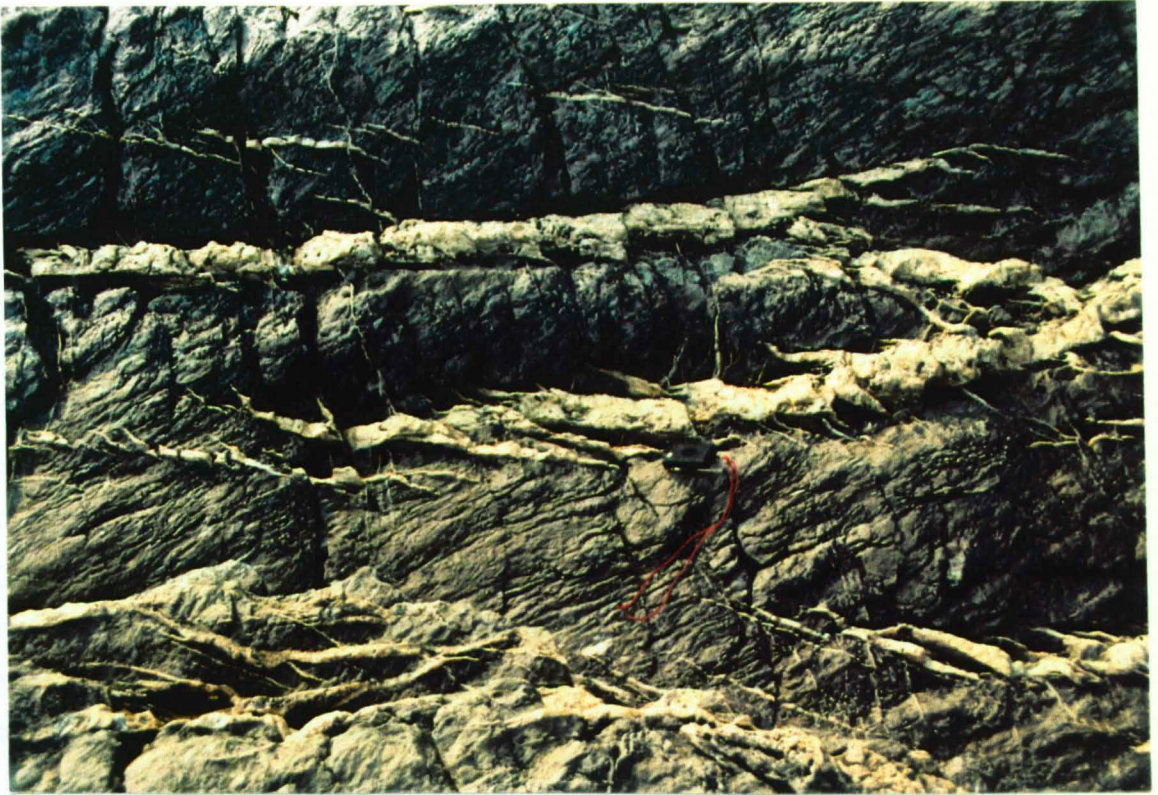


Plate 4.29 Quartz vein array indicating dextral shear in the Warren Formation, The Warren (SX 5320 4660] .



Plate 4.30 Intersection lineation of the second phase crenulation fabric on a first phase cleavage plane within the Bovisand Formation; Crownhill Bay [SX 4925 4980]. Looking north.

a function of progressive thrust development towards the foreland (see Fig. 4.36). This case is similar to that described for the Moine Thrust zone (Coward and Potts, 1983). These authors discuss how the generation of lower later thrusts may cause higher level thrusts to undergo several phases of straining. They go on to say that during the development of a thrust zone several generations of cleavage and folds may form locally, all related to the same thrust movement, but generated at the tips of different thrust sheets. Alternatively, Sanderson (1982) discusses the generation of second phase fabrics in association with localised strain variation over thrust ramps. The development of a shear reversal as the hangingwall moves over the ramp will shorten any pre-existing cleavage resulting in the development of a crenulation (second phase) fabric. From the data collected in the study area it is not possible to say which mode of formation applies. However, the origins described in the literature indicate that the second phase structures are of a local phenomenon only, having no regional significance in terms of major deformation episodes.

The Kinematic Indicators

Individual kinematic parameters are seldom totally indicative of the movement direction within an orogen, when used on their own. However, when all are considered a more accurate picture of the transport direction is revealed. Parameters used in this study consist of:

- fold axes and fold morphology
- bedding orientation
- cleavage orientations
- thrust plane orientations
- extension lineations and deformed burrows
- slip vectors
- kink bands
- boudinage
- drag folds
- tension gash arrays

Fold axes and fold morphology

Fold axes have been plotted on a Lambert equal area stereonet (see Figs. 4.4 and

4.5). Fold plunges are gentle to moderate to the SW and NE. In general both first and second phase fold axes trend NE-SW and are perpendicular to the propagation direction of the contractional structures, indicating a movement towards the NW or SE. However, the asymmetry and sense of overturning of the first phase folds and hence their facing direction indicates that the transport direction is to the NW.

Bedding orientation

The general strike of the bedding is ca. NE-SW and the dip directions are dominantly to the SE and less commonly to the NW. These relationships are shown on the stereoplots in Fig 4.13. The stereoplot for the Meadfoot Group rocks of Crownhill Bay (Fig. 4.13) is slightly asymmetric and the poles to bedding are aligned along a profile plane. The pole to this plane indicates the position of the hypothetical regional fold axis ($00^{\circ}/050^{\circ}$). The poles to bedding on the stereoplot for the Dartmouth Group rocks between Andurn Point and Heybrook Bay all fall in the NW quadrant of the stereonet. This is due to their presence on a single limb (SE dipping) of a regional fold. The plots indicate that the axis of shortening during deformation of these rocks is NW-SE.

Cleavage orientation

The general strike of the cleavage is ca. NE-SW and the dip directions are dominantly to the SE and only rarely to the NW. This is indicated by the position of the average cleavage plane on the stereoplots in Fig. 4.14. The position of the average cleavage plane varies between the two sub-areas shown in this figure. This is a function of a gradual steepening of cleavage from the northern part of the study area (Andurn Point) to the southern part (Erme Estuary). The regional shortening direction implied by the above data is oriented NW-SE, perpendicular to the general cleavage trends.

Thrust plane orientation

The thrust planes, although sometimes folded (see Figs 4.15 and 4.16), generally dip to the SE and strike NE-SW. However, attitudes are variable in the case of low angle or sub-horizontal thrust planes. Plotting thrust traces provides additional information on regional transport directions. Fig. 4.17 shows a stereoplot of poles to thrust planes observed in the

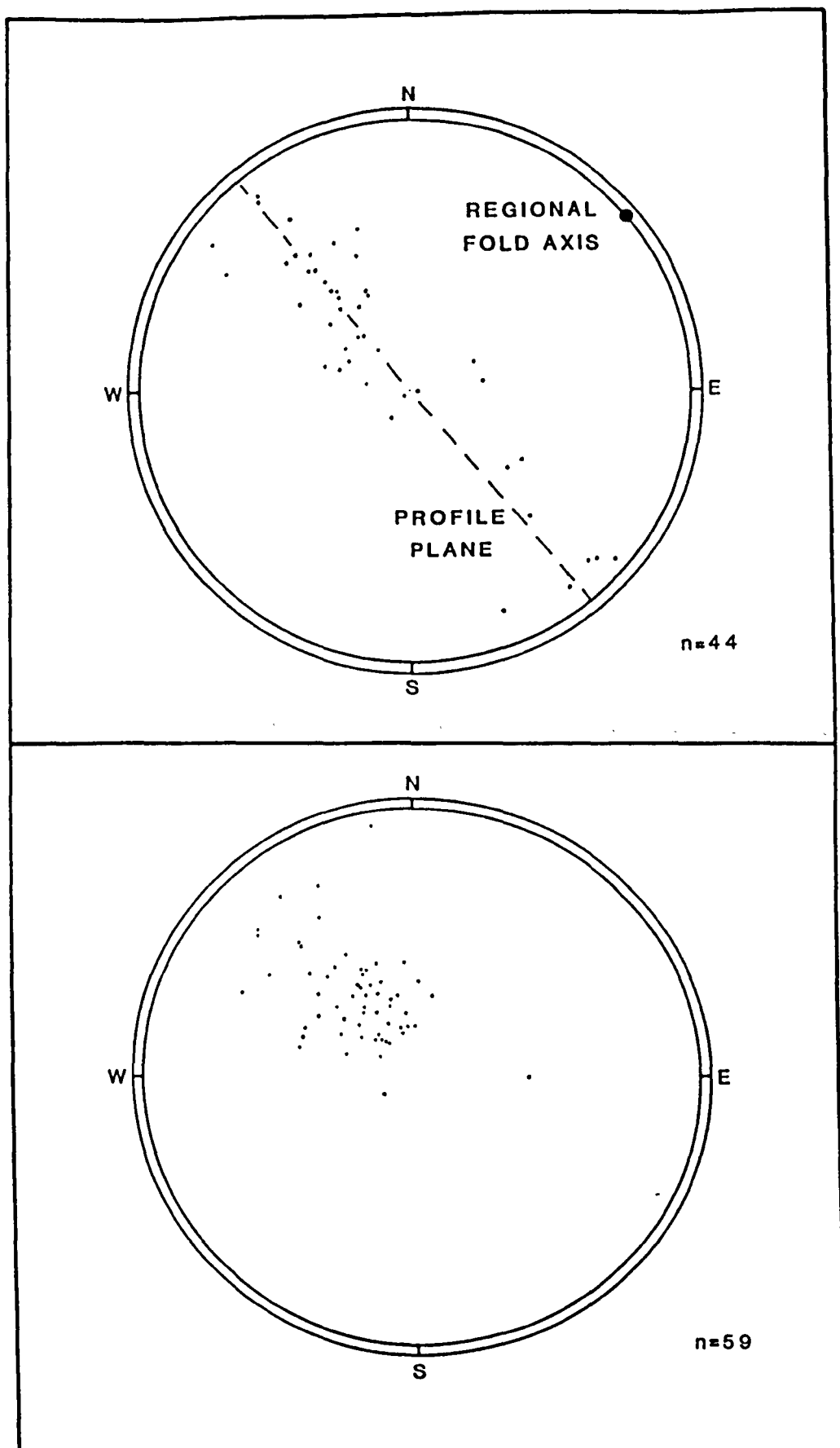


Fig. 4.13 Stereoplot of poles to bedding observed in the Meadfoot Group rocks at Crownhill Bay (top) and in the Dartmouth Group rocks between Andurn Point and Hazybrook Bay (bottom).

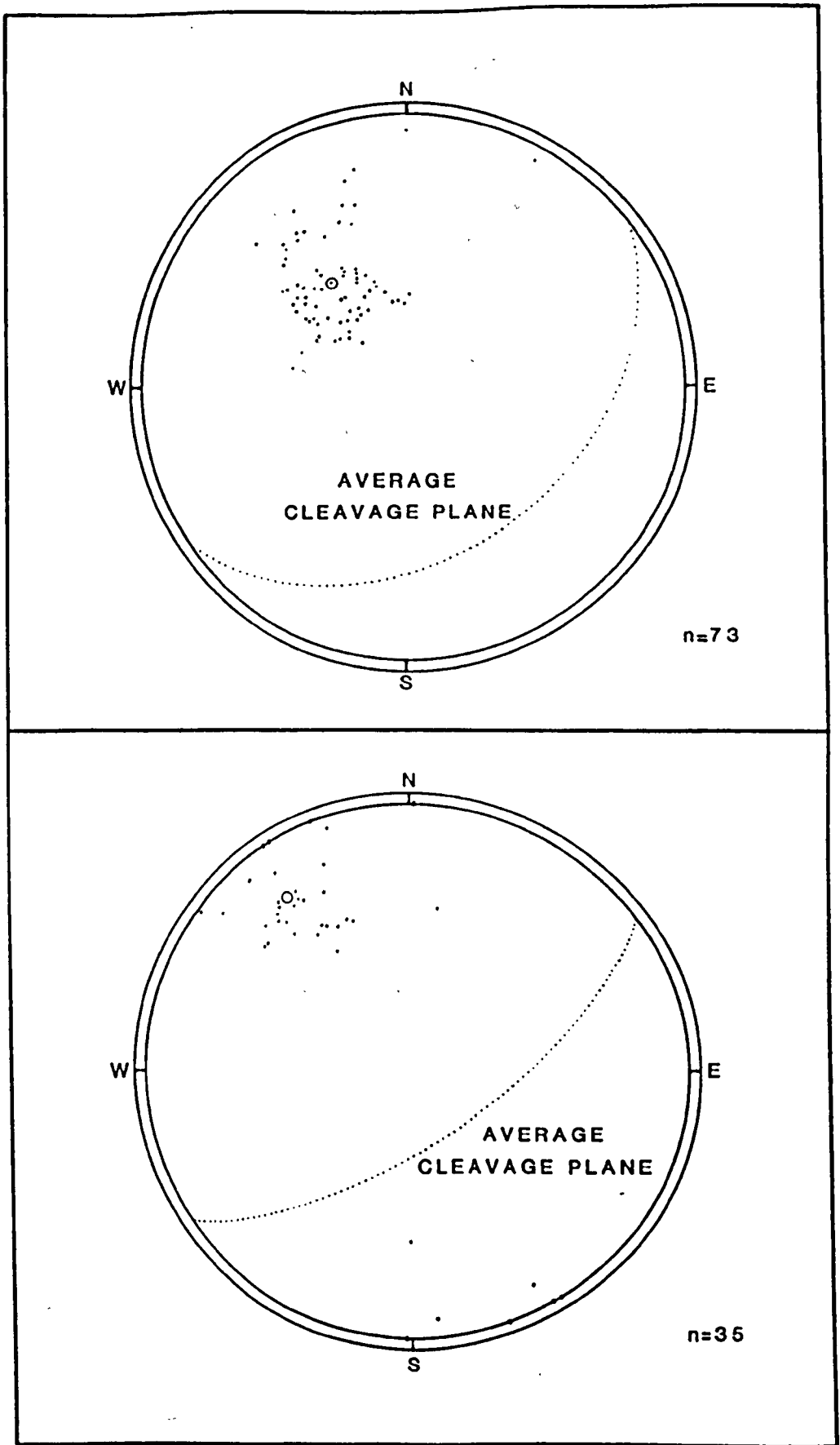


Fig. 4.14 Stereoplot of poles to the first phase cleavage observed in the Dartmouth Group rocks between Andurn Point and Heybrook Bay (top) and along The Warren between Gara Point and the Erme Estuary (bottom).

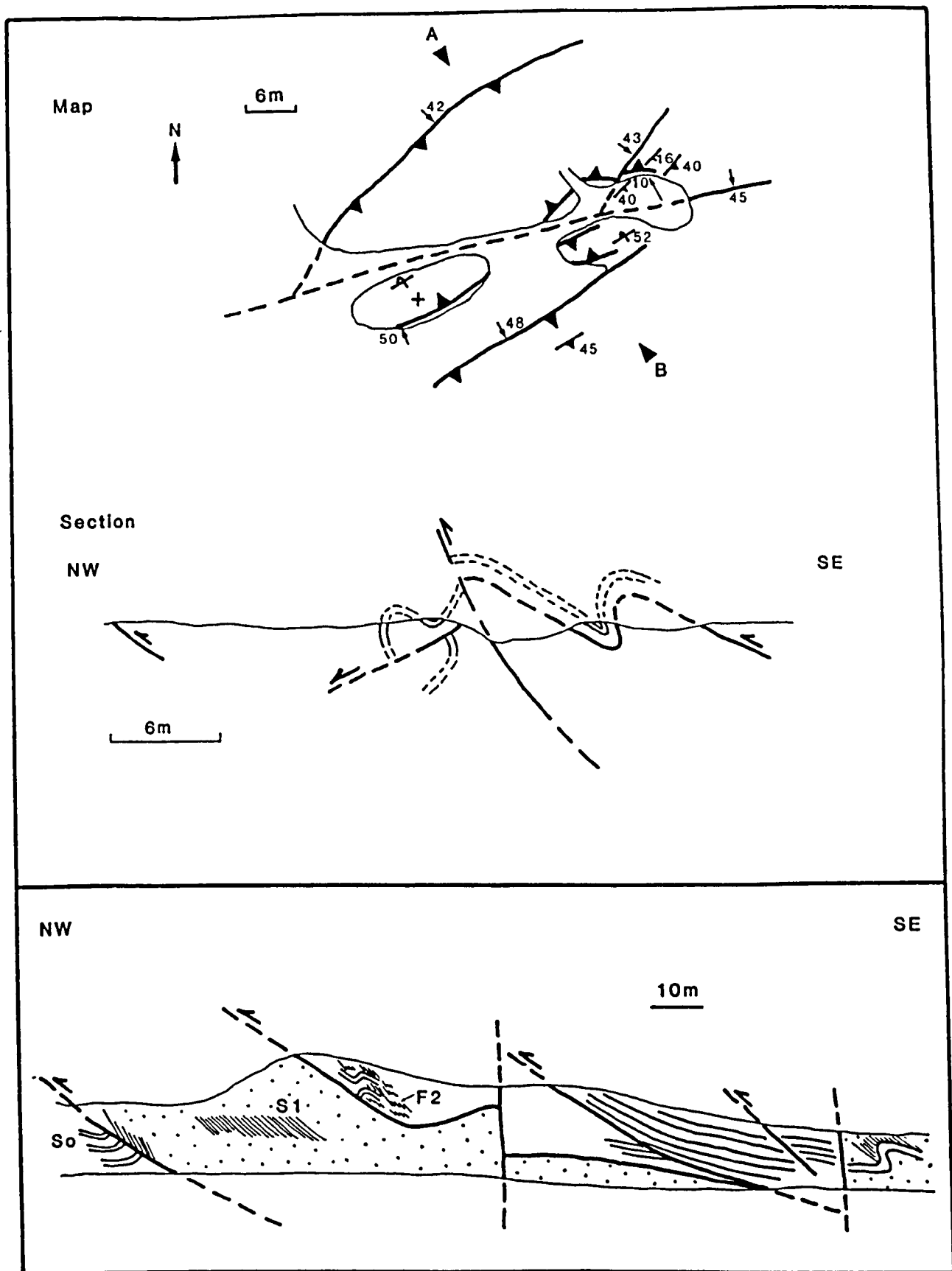


Fig. 4.15 Detailed maps and sections of fold and thrust relations in the Dartmouth Group rocks near Renney Rocks [SX 4925 4875] (top) and Westlake Bay [SX 4925 4920] (bottom).

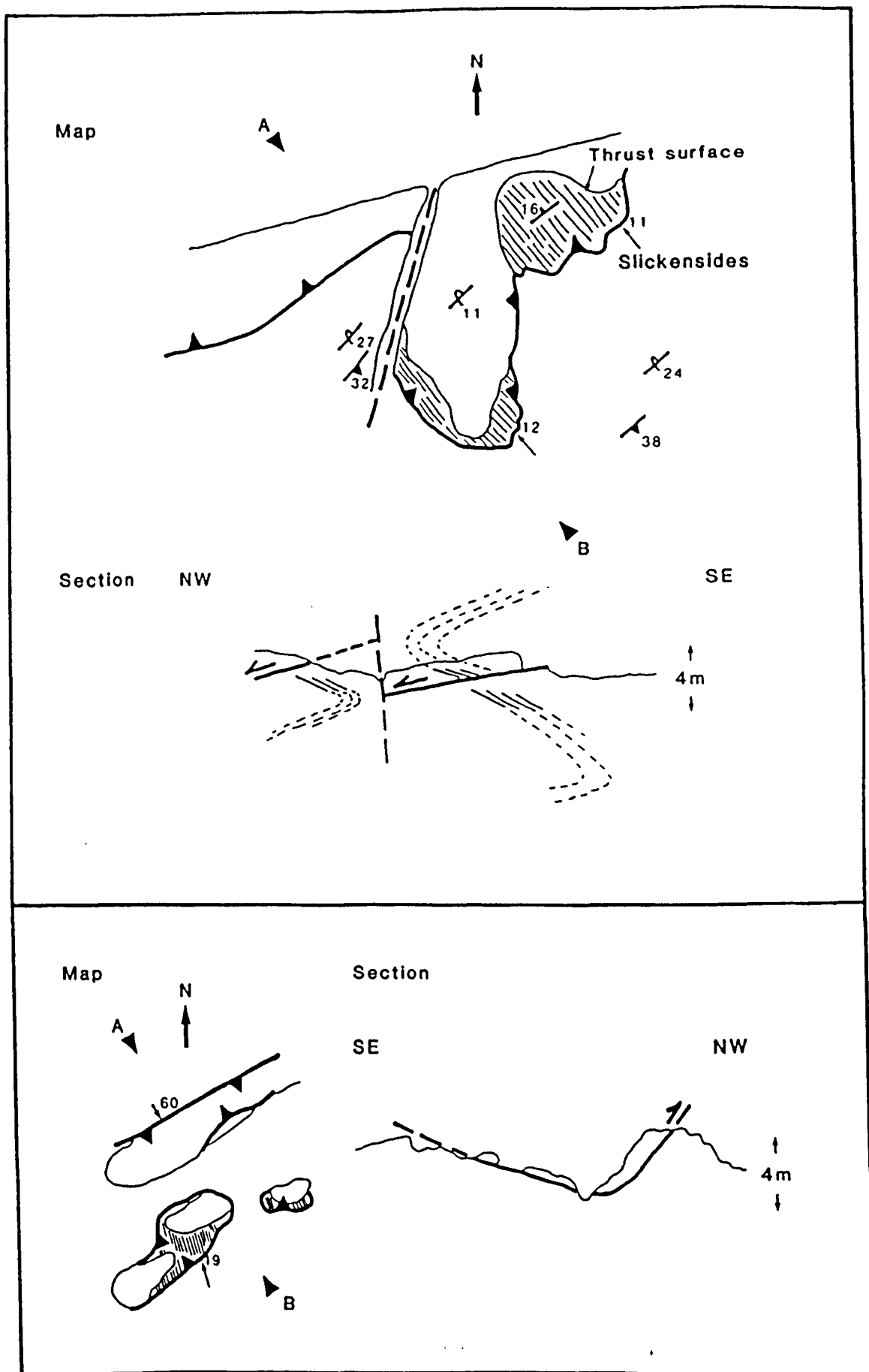


Fig. 4.16 Detailed maps and sections of fold and thrust relations in the Dartmouth Group rocks near Renney Rocks [SX 4920 4890].

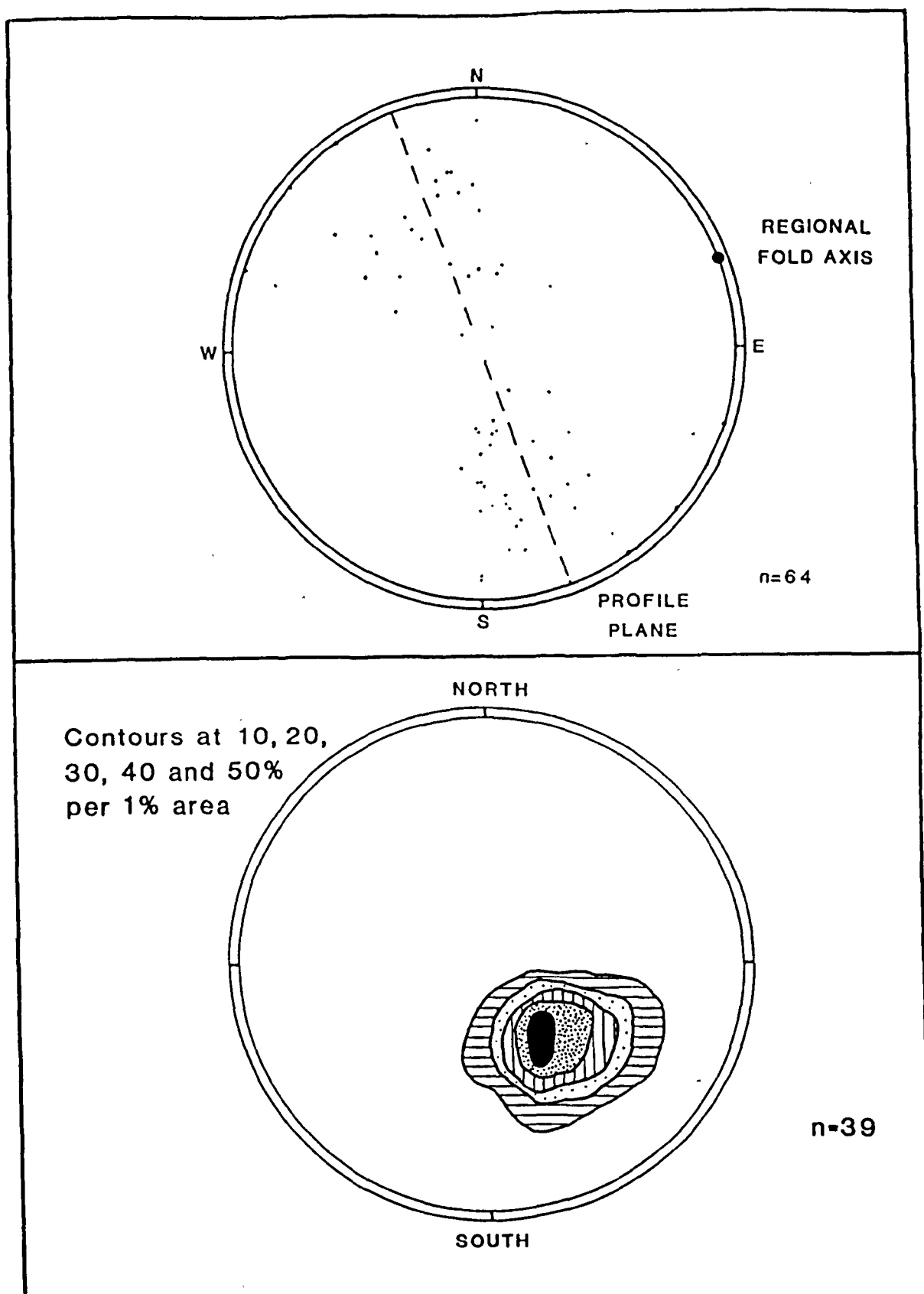


Fig. 4.17 Stereoplot of poles to thrust planes observed in the southern zone.

Fig. 4.18 Stereoplot of re-oriented burrows observed in the Dartmouth Group rocks of the southern zone.

southern zone. On this plot the poles lie on a great circle implying that many thrusts are folded or backthrusts are common. Field evidence points to the former. The regional fold axis is determined by plotting the pole to the profile plane. The contact between the Dartmouth Group rocks and those of the Meadfoot Group (BGS sheet no. 349) between [SX 5660 4760], near Noss Mayo, and Modbury [SX 6575 5160] is an example of one such thrust. Its trend is 070° to 250° . The same tectonic contact with a similar trend occurs inland of Crownhill Bay [SX 4925 4980]. A NW-SE shortening direction is indicated from the analysis of thrust faults.

Extension lineations and deformed burrows

Extension lineations occur as pyrite and quartz intergrowths and form elongate mineral aggregates on cleavage planes (Pls 4.31 and 4.32). In thin section these intergrowths are clearly visible (Pl. 4.33) and the quartz produces pressure shadows around the cubic pyrite crystals. Aggregates of quartz and chlorite are also present and in this case the chlorite forms as a pressure shadow on either side of the host quartz grains.

Burrows are a common feature within the rocks of the Dartmouth Group and these have been rotated and flattened and lie down dip on the cleavage plane (Pl. 4.34). They are also oriented perpendicular to the first phase fold axes. During the second phase folding the burrows remain oriented down dip on both limbs of the folds and also remain perpendicular to the second phase fold axes (Pl. 4.35).

Mineral aggregates and deformed burrows have been plotted on equal area stereonet (Figs. 4.18 and 4.19) and these indicate a general plunge to the SE implying transport to the NW.

Slip vectors

The polished surfaces consisting of a fibrous growth of quartz or calcite are generally referred to as slickensides and are observed on both bedding and fault planes. The clastic sequences of the study area contain quartz slickensides whilst the limestone sequences contain calcite slickensides. Slickenside surfaces always exhibit parallel ribbing which is elongate in one direction and parallel to the direction of fault displacement (Durney and Ramsay, 1973). These structures can therefore be used to determine the direction of slip/displacement.

From plotting the plunge and direction of plunge of the slickensides, an accurate

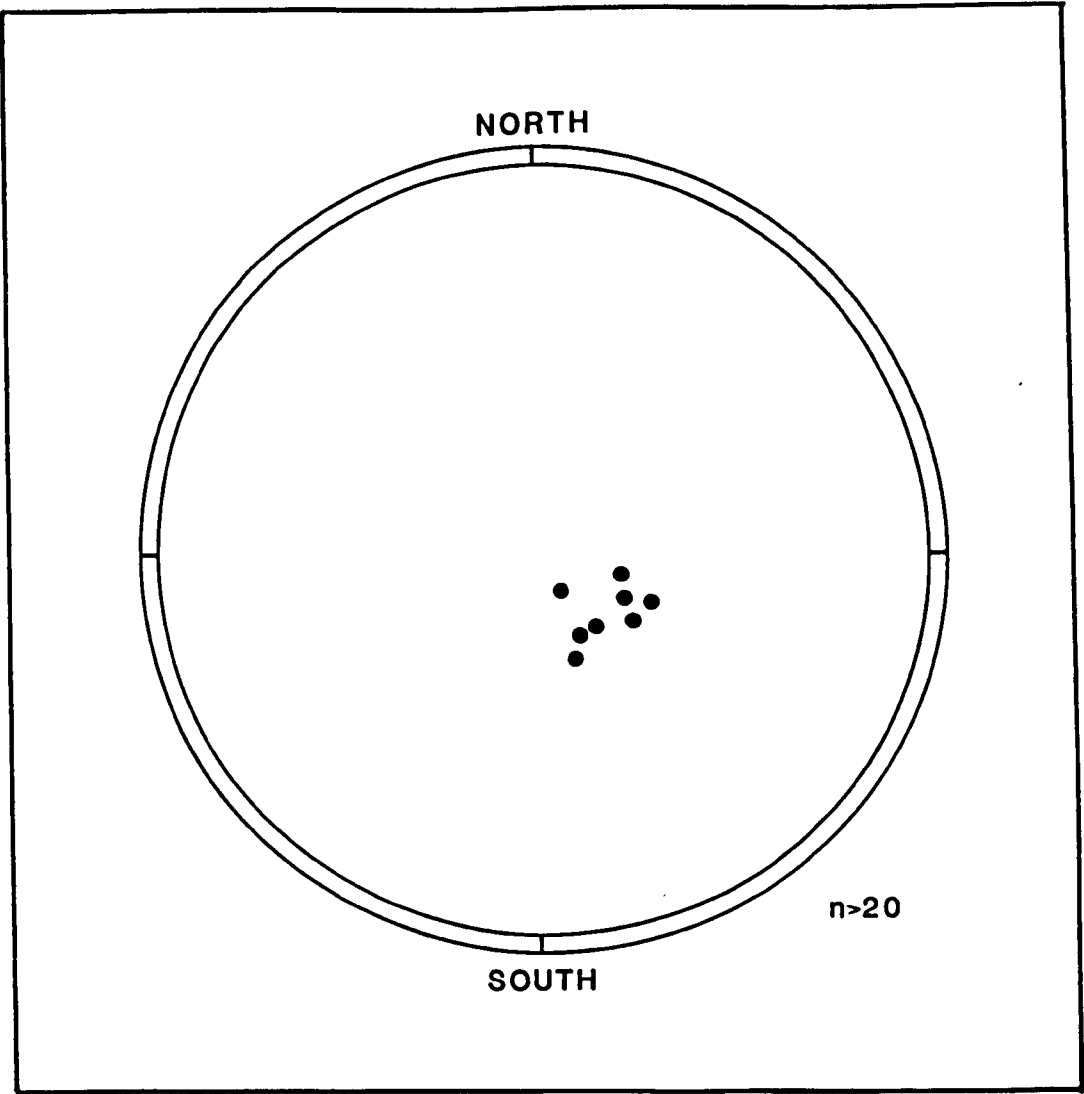


Fig. 4.19 Stereoplot of mineral lineations observed in the Dartmouth Group rocks of the southern zone. Each point represents multiple readings.



Plate 4.31 Down-dip extension lineation defined by pyrite and quartz intergrowths in the volcanoclastics of the Yealm Formation; Erme Estuary [SX 6145 4760]. Looking north west onto first phase cleavage plane.

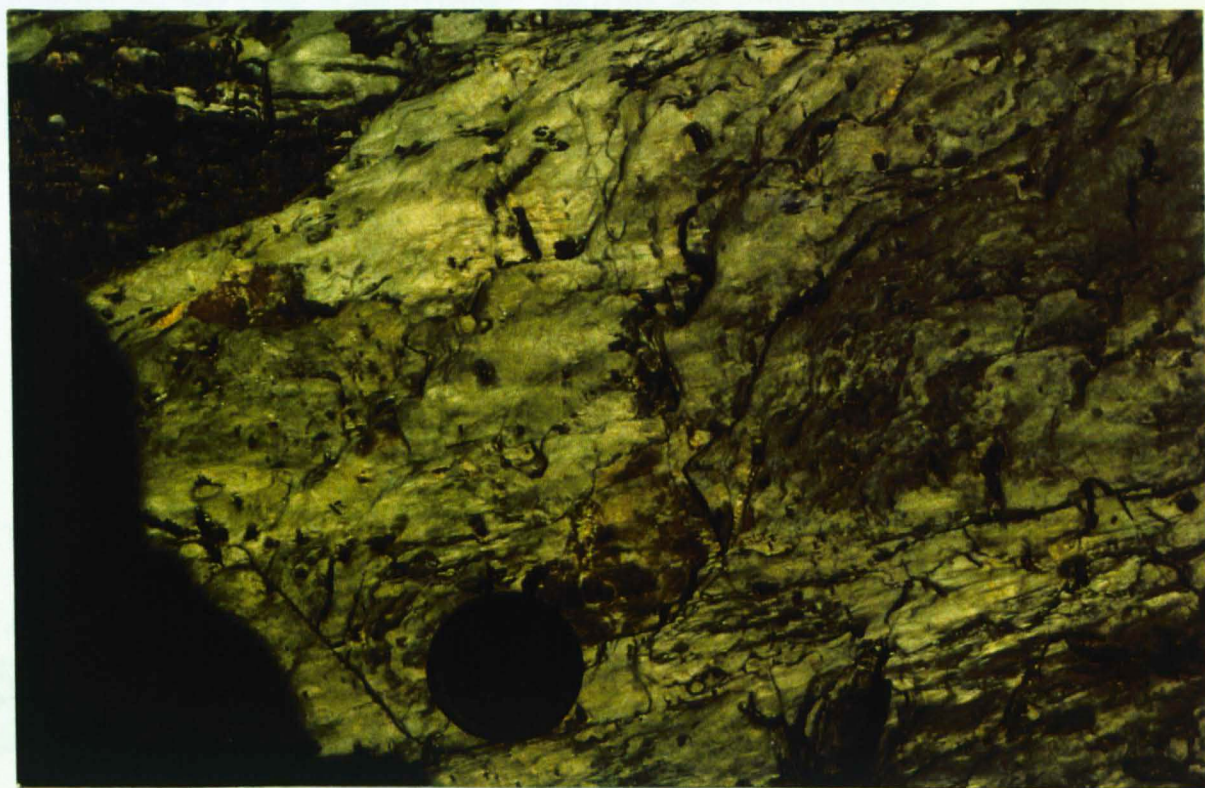


Plate 4.32 As 4.31 in the Yealm Formation exposed to the east of Wadham Rocks [SX 5800 4700].

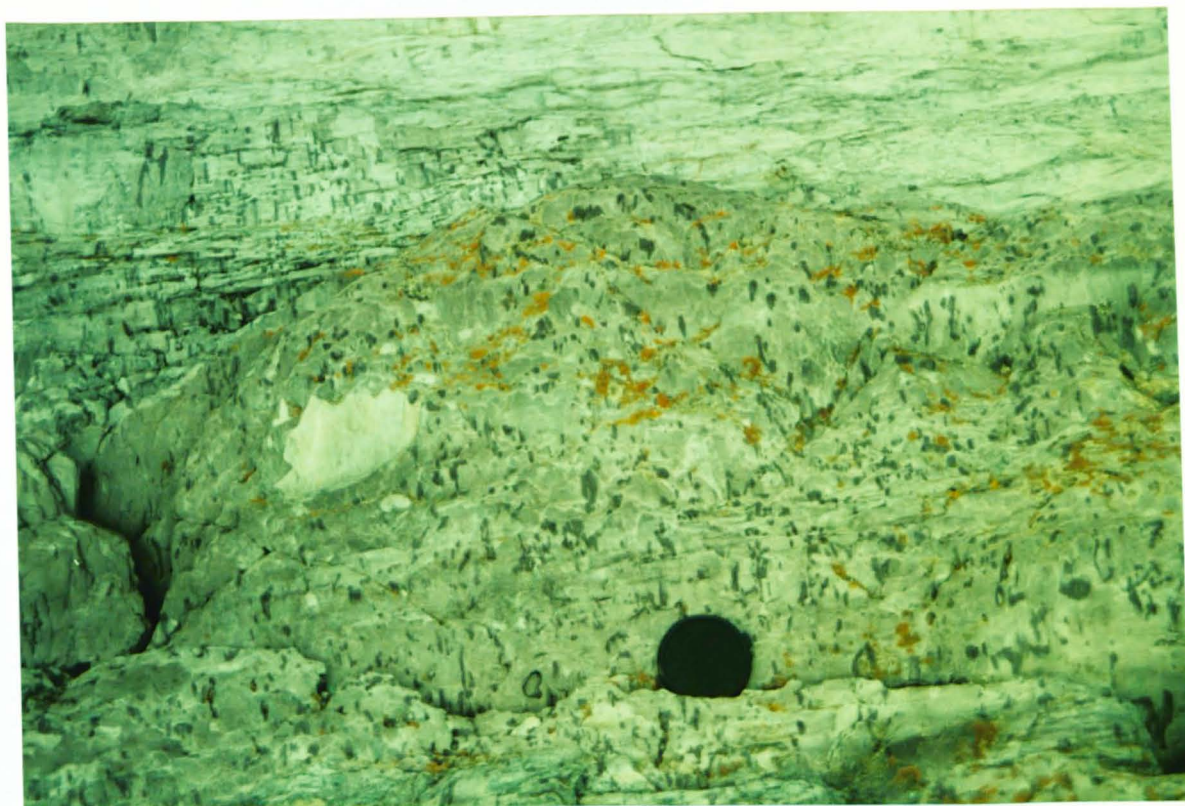


Plate 4.33 Down-dip lineation defined by re-oriented burrows within siltstones of the Warren Formation; Blackstone Point [SX 5350 4620]. Looking north west onto first phase cleavage plane.

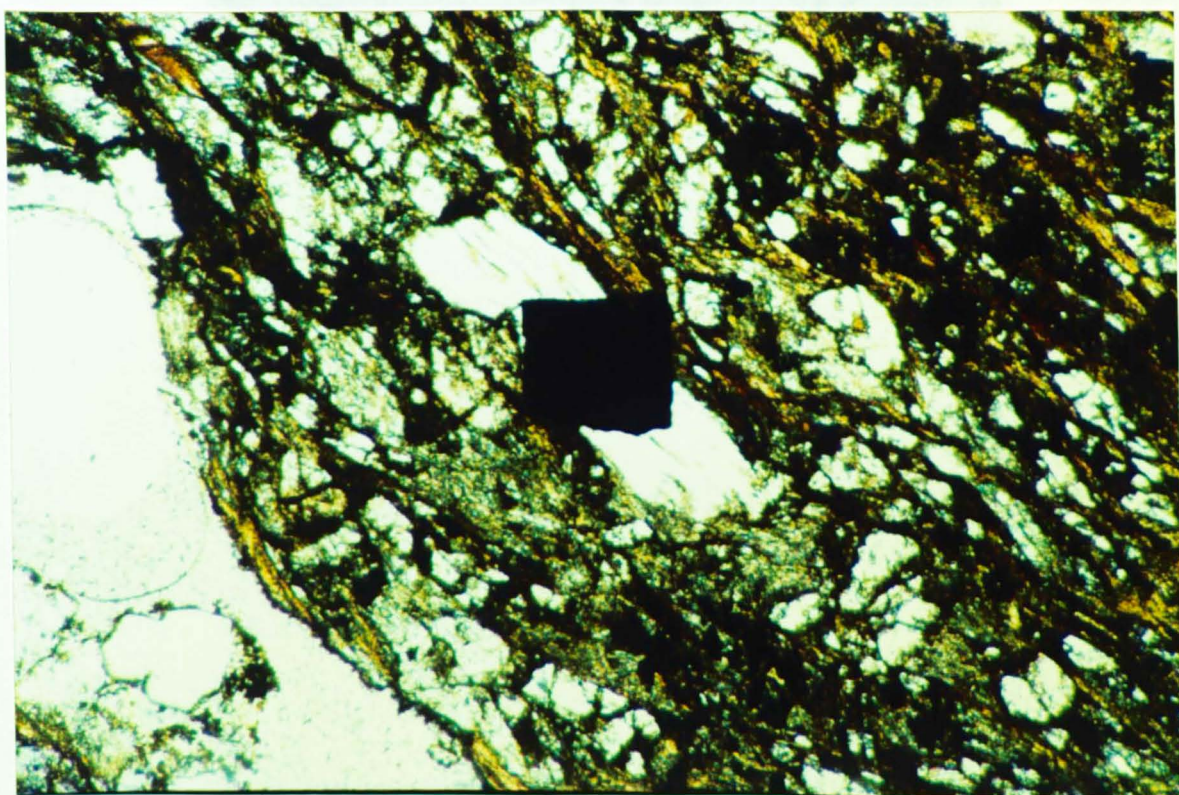


Plate 4.34 Photomicrograph (x64) of pyrite and quartz intergrowth. The quartz grows in the pressure shadow region of the pyrite cube; plane polarised light. Yealm Formation, Carswell Cove [SX 5860 4715].



Plate 4.35 Re-oriented burrows folded by second phase folds. Burrows are orthogonal to the second phase fold axis implying co-axial nature of the folding, Warren Formation; Blackstone Point [SX 5350 4620]. Looking north east.

picture of the movement history during orogenesis (Figs. 4.20 and 4.21) can be deduced. This is straightforward when planes display one direction only. However, some planes show repeated evidence of movement (hence reactivation), and slickenside surfaces overprint each other. Clearly the uppermost slickenside records the last phase of movement. The slickenside thus records an axis of movement but if they are stepped then they define the movement direction precisely. However stepping is only rarely preserved.

On folded bedding planes the slickensides are perpendicular to the associated fold axes and indicate the orientation of flexural slip in the fold. On thrust planes the slip vectors record the direction of movement of the rocks in the hanging wall over those of the footwall. In the southern zone of the study area, the slickensides plunge towards the SE on SE dipping thrust surfaces and to the NW on NW dipping surfaces. The latter case occurs when thrusts are folded resulting in NW and SE dipping limbs or in the case of backthrusts.

The above data shows that the transport direction is to the NW or SE, however, their down dip nature along with associated fold/thrust structures show that movement was to the NW. Slickensides are also observed on vertical compartmental faults where they are sub-horizontal and trend NW-SE, a direction parallel to the trend of the associated faults (see below).

Kink bands

Kink bands are local in occurrence and invariably deform the slaty cleavage in the Lower Devonian slates. They have been described as the F4 phase by Hobson (1976a) and there is no reason to doubt that they form in the latter stages of deformation. They are more common in the southern part of the southern zone and in places they totally disrupt the slates. Their trend is consistently NW-SE (Pl. 4.36). This trend is sub-parallel to the regional transport direction as indicated by other data.

Other kink bands are present in the far south of the southern zone. These appear to have a different mode of formation. The orientation of their kink bands indicate a movement direction to the SE (Pl. 4.37). They are also considered to be late phase but form during back steepening, a by-product of NW directed thrusting and progressive thrust stacking. These kink bands belong to a series of accommodation structures. Other accommodation structures such as cleavage, faults, drags and folds have a similar origin and also indicate southerly directed movement.

Contours at 3, 5, 7, 9,
11, 13, 17

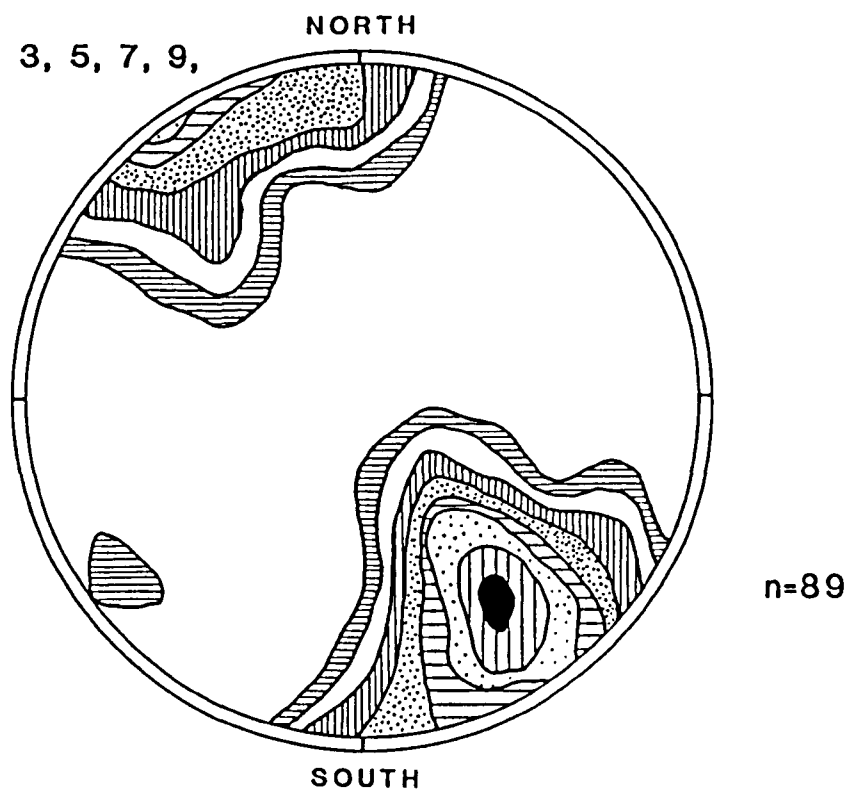


Fig. 4.20 Stereoplot of slip vectors observed on bedding planes and thrust faults within the Devonian sequence of the southern zone.

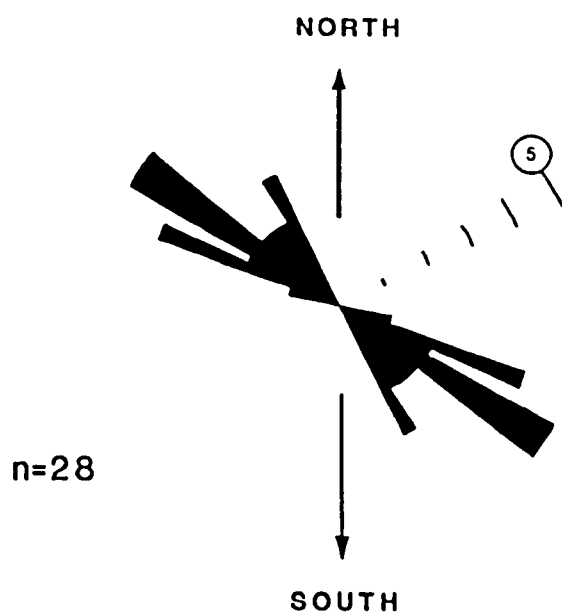


Fig. 4.21 Rose diagram of compartmental fault orientations measured in the field and from published BGS maps of SW Devon and SE Cornwall.



Plate 4.36 Kink bands deforming cleaved black slates of the Bovisand Formation; Armyr Cove [SX 6410 4550]. Looking north west.



Plate 4.37 Kink folds in the Meadfoot Group slates at Armyr Cove [SX 6410 4550]. Looking north east.



Plate 4.38 Boudinaged tuff bed in the Bovisand Formation; Bigbury Bay [SX 6600 4330]. Looking north east.

Boudinage

This occurs as a localised pinch and swell feature within competent sandstones and tuff beds contained in pelitic host rocks (Pls 4.38 and 4.39). Under more intense deformation bed separation occurs producing individual boudins (Pl. 4.40). Within the zone of steep structures (southern zone), at Penlee Point [SX 4430 4875], the boudins are separated by quartz infills.

Due to the mode of formation the boudinage takes on two forms or orientations. However, both can be explained as having formed under the same regional deformation conditions with the same axis of contraction. The two forms are in turn associated with folding (fold boudinage) and thrusting (thrust boudinage) (see Fig. 4.22). They are differentiated by their relative orientation and association to structural features (folds and thrusts) in their immediate vicinity. Fold boudinage is common whilst thrust boudinage is only rarely seen.

In fold boudinage the long axis of the boudin is perpendicular to the direction of orogenic shortening but with thrust boudinage the long axis of the boudin is parallel to the compression direction (see Fig. 4.22). Thrust boudinage is so-called due to the association with nearby thrust faults and the orientation of the long axis of the boudin being parallel to the direction of movement (see Wilson, 1961). However, fold boudinage is the more common type described in the literature and is also more common in the study area. In this case the long axes of the boudins are oriented parallel to the regional and local fold axes and perpendicular to the transport direction. They are commonly found on fold limbs, and are related to local extension on the fold limbs.

The local principal stress directions can be determined using the boudinage structures assuming that they are symmetrical structures. Although the two forms described here exist in the same area from a maximum stress direction (P-max) oriented SE-NW (136° to 316°). Hence, they are products of the same regional stress field, however local variations in the orientation of the stress axes are responsible for producing thrust boudinage. P-max determined from boudinage coincides with the 'z' direction of the strain ellipsoid measured from deformed reduction spots. The localised extension direction (P-min) on fold limbs is oriented NW-SE and is parallel to the regional transport direction and orthogonal to the fold axis. However, in thrust boudinage the extension direction (P-min) is oriented NE-SW (see Fig. 4.22). Extension can occur parallel to the regional shortening direction on fold limbs (Fig. 4.22) but in thrust boudinage the extension direction is perpendicular to regional

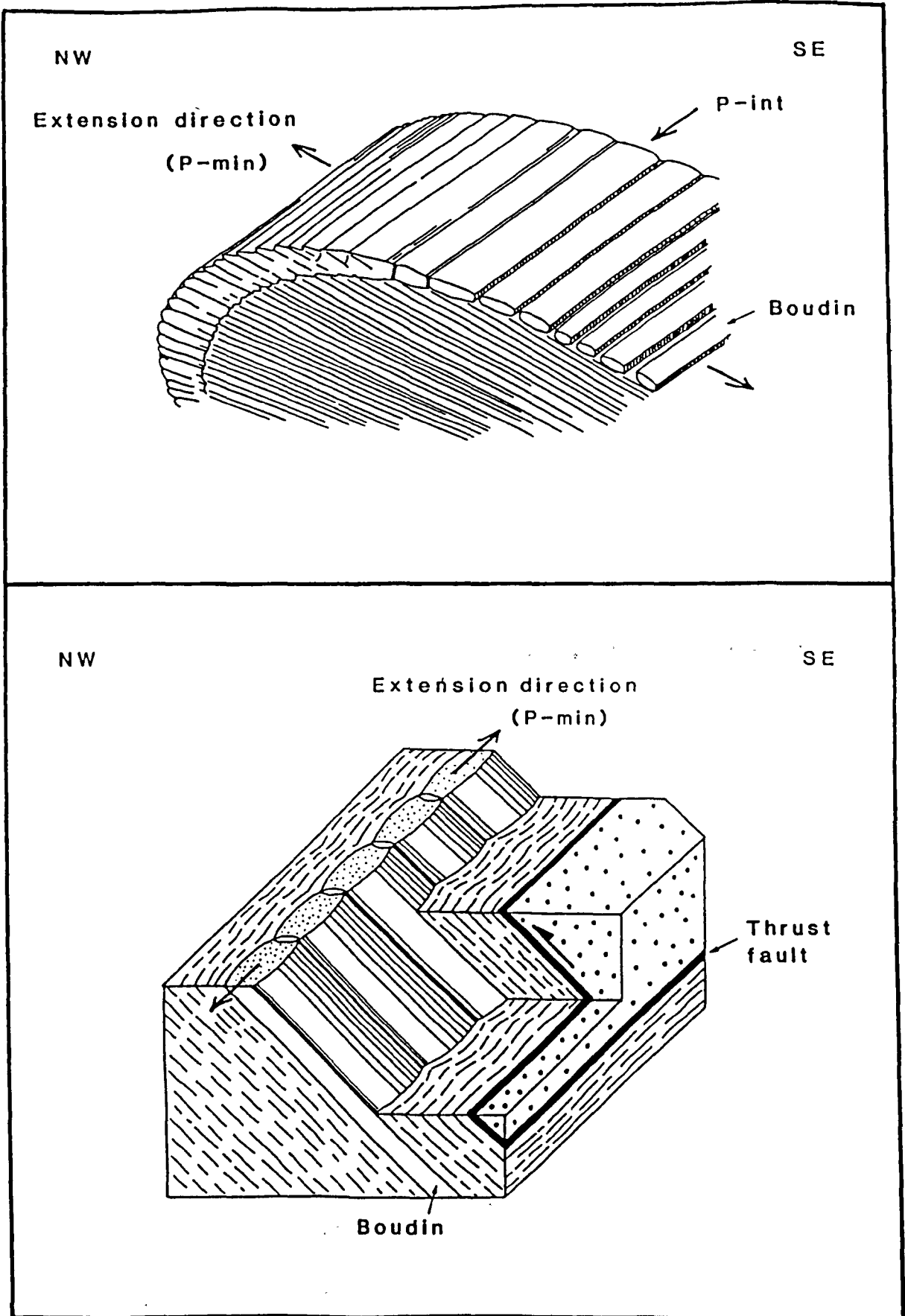


Fig. 4.22 Fold and thrust boudinage geometries observed in the southern zone (after Wilson, 1961).

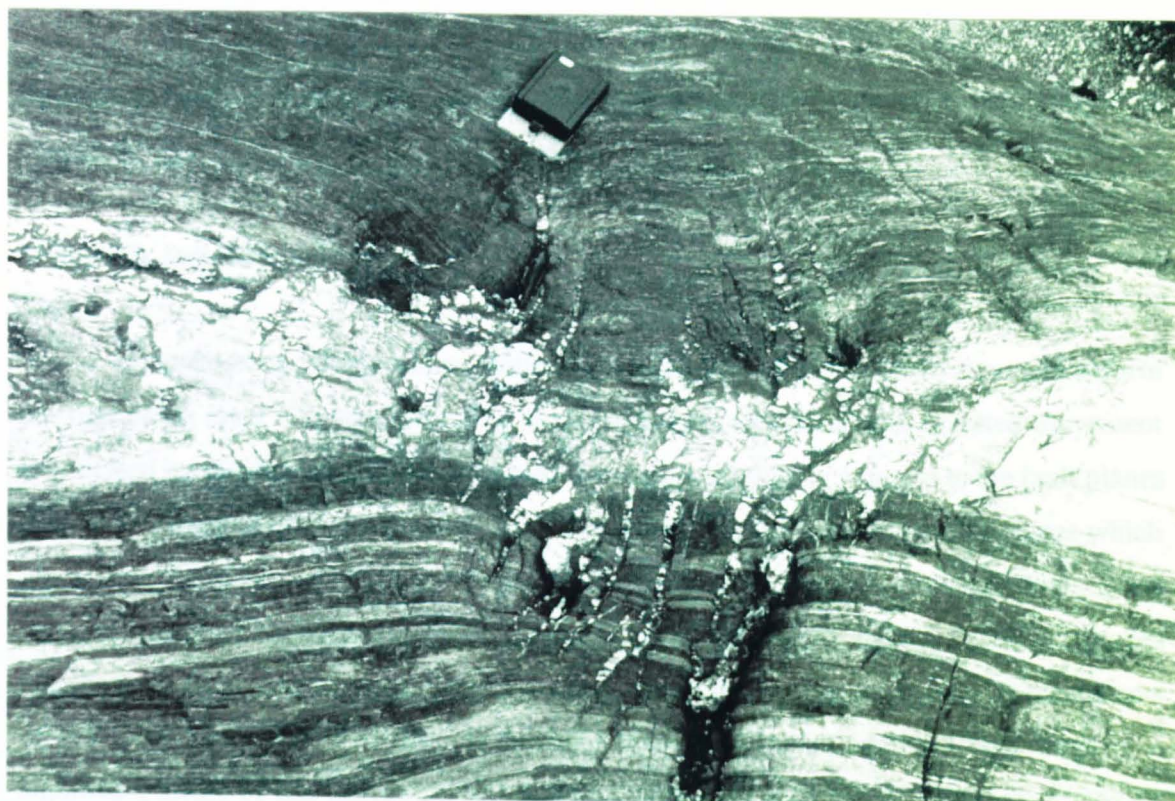


Plate 4.39 Close up of Pl. 4.38.



Plate 4.40 Quartz fills separating boudins in the Dartmouth Group at Penlee Point [SX 4425 4875]. Looking west.

shortening. This change in the orientation of the stress axes may be a direct result of overthrusting.

Drag folds (adjacent to faults)

Drag folds occur adjacent to faults in the steep part of the southern zone and deform the first phase slaty cleavage (post F1). Both southward and northward directed movement is indicated by the geometry of the deformed cleavage immediately adjacent to the fault planes (Fig. 4.23) and motion is generally of a reverse sense. The faults are low angle planes which dip both to the north and south and displacement across them may be very small (only a few cms). A system of fractures also occur in association with the faults and have similar attitudes but show no displacement or deformation of adjacent fabrics. Although total displacements of the fault and fracture systems is minimal their profuseness indicates that there is a significant phase of late northward and southward directed movement. The former may be regarded as resulting from out-of-sequence north directed motion related to the main northwards directed deformational event. The southward movement is an opposite sense to that usually encountered and is possibly related to late phase steepening during progressive stacking of the foreland propagating thrust sequence.

Tension gash arrays

These form as conjugate sets (Pl. 4.41) or as solitary arrays (see Fig. 4.24 and Pls 4.27, 4.28, 4.29 and 4.42) and are filled with quartz or calcite depending on whether the host rock is composed of sandstone or limestone. Conjugate sets form in the same way as the more brittle conjugate shear fractures (see Price, 1966). The bisector of the acute angle of the conjugate pair indicates the direction of main compression (towards 323° as seen in Fig. 4.24). Solitary tension gash arrays follow one of the orientations (113° to 293° or 173° to 353°) depicted by the conjugate pair and are sometimes themselves paired with a fracture. The stress axes associated with these structures are shown in Fig. 4.25. P-min bisects the obtuse angle of the conjugate set ($00^\circ/054^\circ$) and P-int is oriented NW-SE ($30^\circ/143^\circ$), both are contained within the plane of bedding. P-max is the axis intersecting P-min and P-int and is contained within the vertical plane oriented NW-SE ($60^\circ/323^\circ$) (Fig. 4.25). The above relationships indicate shortening towards the NW.

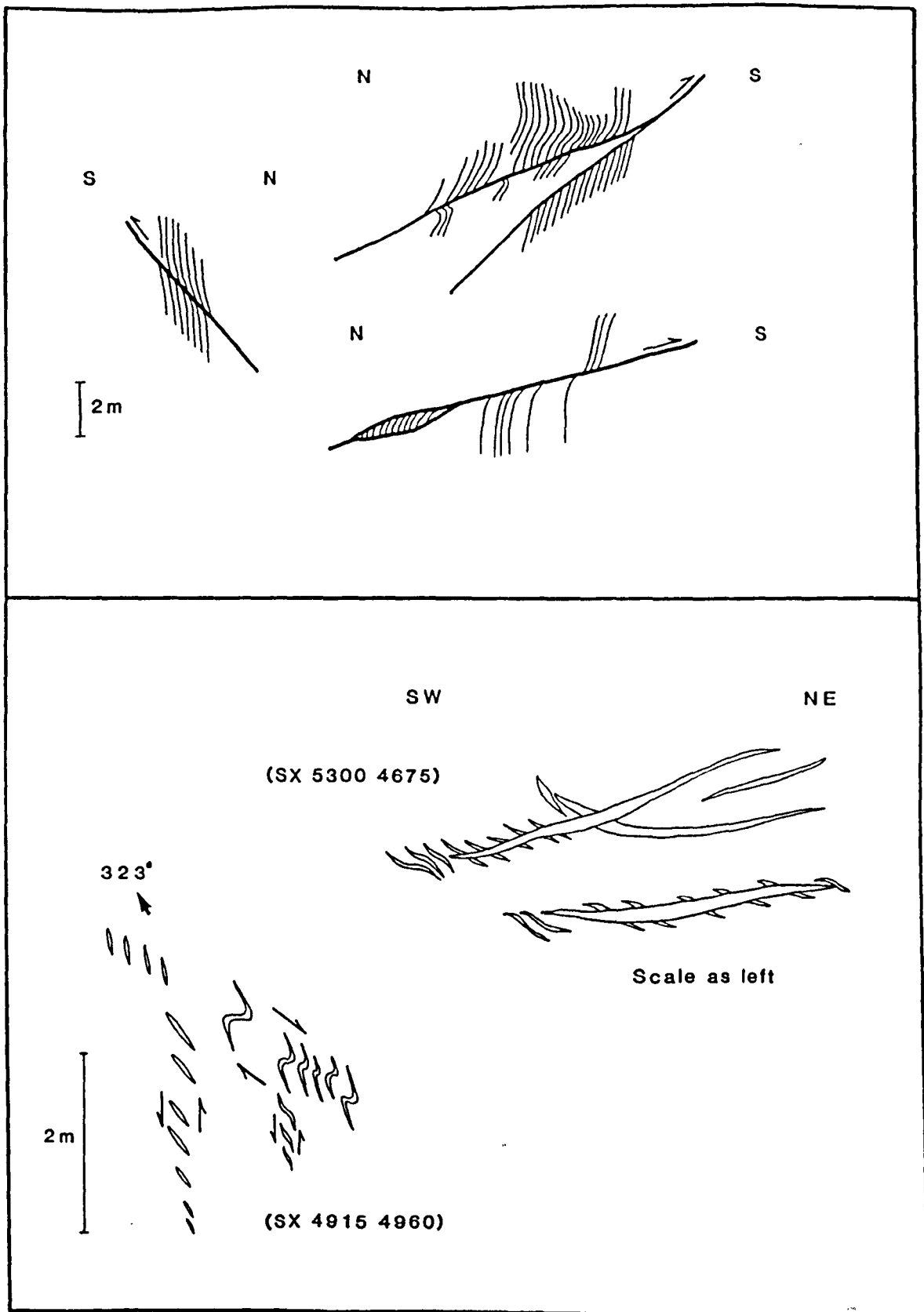


Fig. 4.23 Deformed cleavage adjacent to north dipping fault planes observed in the far south of the southern zone [SX 6745 4100].

Fig. 4.24 Line drawings of quartz vein arrays observed in the Dartmouth Group rocks of the southern zone. Looking down onto bedding planes.

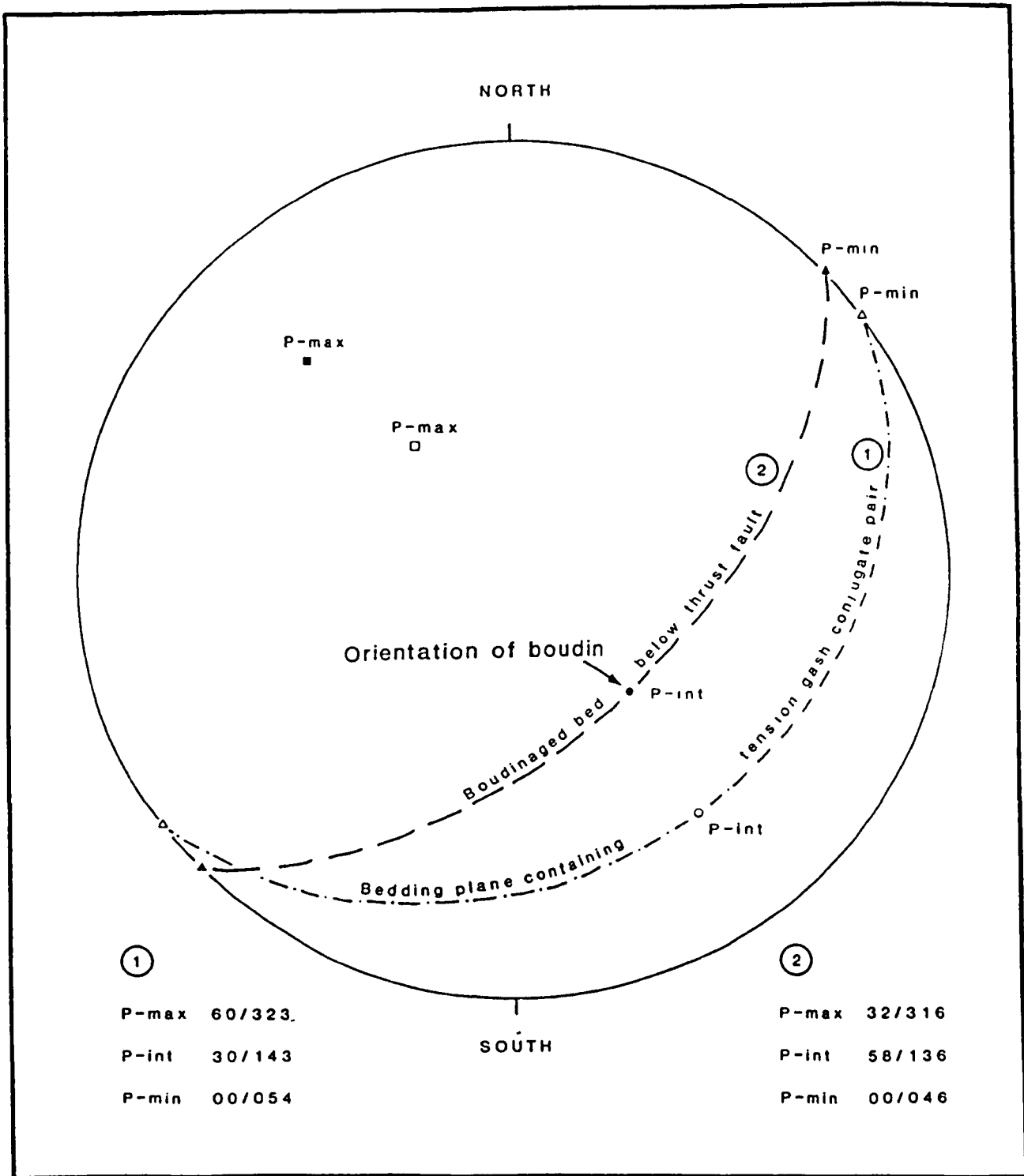


Fig. 4.25 Stereoplot showing the orientation of stress axes obtained from boudinaged beds and tension gash arrays.



Plate 4.41 Conjugate set of quartz vein arrays in the Renney Rocks Formation between Andurn Point [SX 4920 4975] and Westlake Bay [SX 4925 4920]. Looking north west.

Compartmental faults

A NW-SE suite of steeply dipping faults transect the SW England peninsula (Fig. 4.20) and some reach as a least one small scale (see Pl. 4.43) in the south west.

The spacing of the faults and the nature of the movement, they are referred to as compartmental faults. Their form may be variable, but they are generally steeply dipping and are associated with dextral movement. The movement is generally dextral, but in some cases it is sinistral (see Fig. 2.6). This is the movement of the blocks of rock relative to each other. The development of the compartmental faults is related to the Variscan orogeny and the thrusting of the Variscan orogeny. The compartmental faults are considered to be the kinematics of the Variscan orogeny (Fig. 4.21). Thus, the compartmental faults will explain why almost all the compartmental faults in the south west are still active. The compartmental faults are also referred to as the compartmental faults.



Plate 4.42 Shear fractures indicating dextral motion; Andurn Point [SX 4920 4975]. Looking south east.

Compartmental faults

A NW-SE suite of steeply dipping faults transect the SW England peninsula (Fig. 4.26) and occur both on a large and small scale (see Pl. 4.43) in the study area.

The approximate NW-SE trend, steep to sub-vertical attitude and the strike slip nature of the faults divide the rocks of this area into a series of compartments. Hence, they are referred to as compartmental faults. Similar structures exist in each compartment but their form may be unique to each compartment. If, after restoration of the strike-slip movement, fold axes, fault traces and stratigraphic contacts do not match up between compartments (see Fig 2.6), the faults can then be said to have formed during the main thrusting event. This would imply that deformation proceeded in each compartment independently of the movement in adjacent compartments. Faults which terminate against thrusts in map form (see Fig. 2.6) are likely to join with them at depth and are thus closely linked in terms of their development. Faults which comply with the above conditions are likely to have formed during Variscan orogenesis and are thus closely related to the system of NE-SW trending folds and thrusts of known Variscan origin. Due to this close association, compartmental faults may be considered as steep lateral ramps as standard lateral ramps usually have much lower fault/bedding cut-off angles. An angle of ca. 20° exists between the transport direction inferred from the kinematic indicators and the average trend of the compartmental faults (see Figs 4.20 and 4.21). Thus if the compartmental faults are truly Variscan in origin this angular difference will explain why almost all of the compartmental faults have dextral displacements. However, in many cases it still remains difficult to prove that these faults have formed during Variscan orogenesis.

As mentioned above, the sense of displacement of these faults as seen today is invariably dextral (right lateral) strike slip, although this may be modified by a component of dip slip attributed to later extension. Some of these dextral faults are commonly referred to in the literature (eg. Sticklepath-Lustleigh Fault, Plymouth Bay Fault and the Portwrinkle Fault). However, a number of previously unrecognised compartmental faults have been observed along the coastal sections examined during this study and although displacements may be small, they nevertheless show dextral shear. Many fractures with the same attitude but with no displacement are also present. Two major faults of this group have been mapped which are not recorded on the existing publishing maps (BGS sheets 349 and 356). The first of these trends NW-SE from Andurn Point [SX 4900 4980], through the foreshore at Wembury [SX 5180 4830] to the Warren [SX 5400 4675] via Cellar Beach [SX 5315 4750]

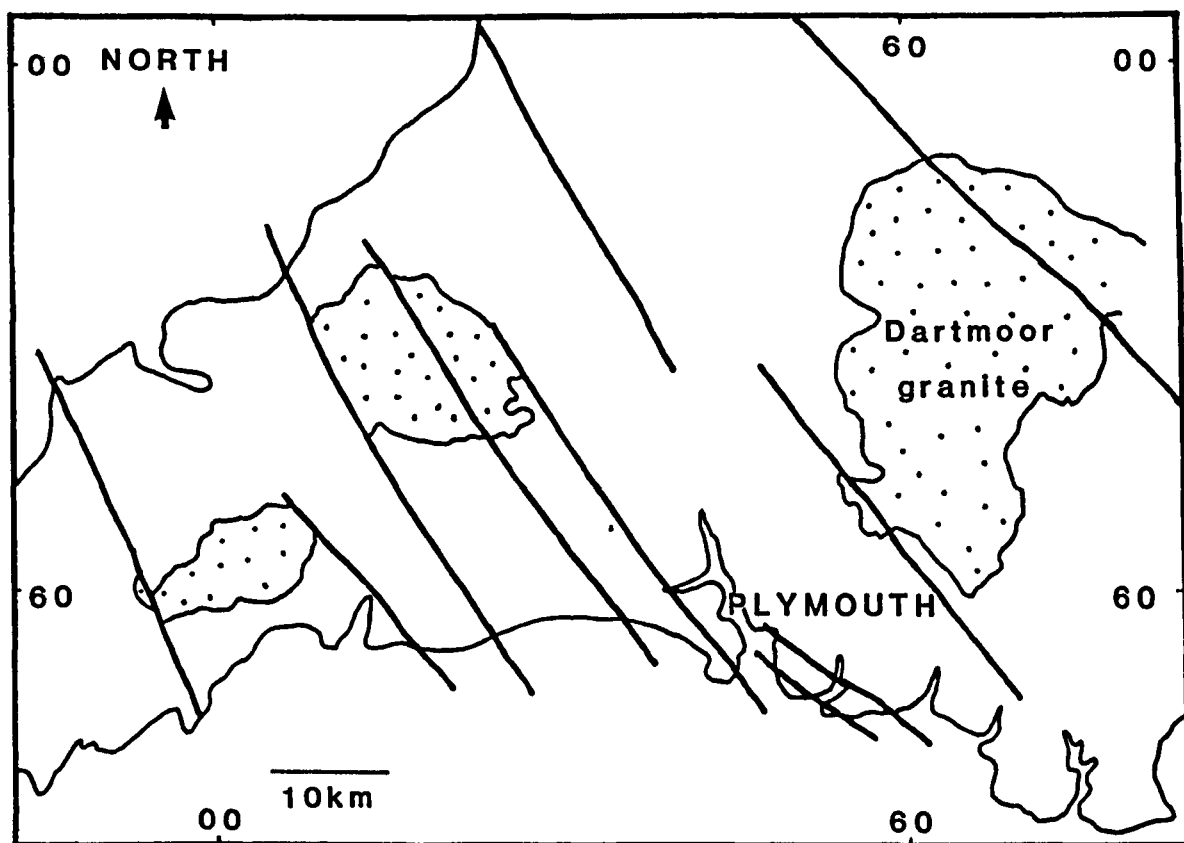


Fig. 4.26 Map showing the distribution of the main dextral compartmental faults in SW England, from this study and published BGS maps (sheet nos. 348, 349, 350, 355 and 356).

Plate 4.43 Small scale compartmental fault displacing a tuff bed in the Bovisand Formation; Avon Mouth [SX 6600 4350] Looking north west.



Plate 4.44 Extensional fault displacing a Variscan thrust. Fault forms parallel to and re-activates the first phase Variscan cleavage; Westlake Bay [SX 4925 4920]. Looking north east.

in the Yealm Estuary [SX 5275 4810]. The limited coastal outcrop however, makes it impossible to determine amounts of displacement and correlate with any geology inland. The second fault trends NW-SE from Owen's Hill [SX 6125 4750] through Wonwell Beach [SX 6175 4725] to the area just south of Scobbiscombe [SX 6300 4690]. It appears that this fault has ca. 1km lateral displacement (see Fig. 5.2). However, the lack of inland exposure hinders any along-strike correlation of structures. The above relationships can be seen in the field maps contained in Appendix 3. It is difficult to prove the age of the small scale faults of this category. Naturally they disrupt other Variscan structures but this only signifies that they may have formed during the Variscan or during post-Variscan (Permian and Tertiary) tectonic events. The best example of compartmentalization is shown in the Jennycliff Bay area where considerable differences in outcrop widths occur on either side of such a fault. This is described in more detail in Section 4.2.2.

The compartmental faults have had a long and continued history of movement and it is likely that some if not all were initiated during the Variscan Orogeny. They have been subsequently re-activated by post-Variscan (probably Permian) extension and also by Tertiary movements as evidenced by the formation of the Bovey Tracey Basin as a sinistral, strike slip, pull-apart basin. A pre-Variscan origin for the faults cannot be ruled out with the structures being initiated during Lower Devonian basin development.

Extensional faults

A system of brittle structures post-date those produced during the Variscan contractional phase of deformation. These are represented by NE-SW and E-W extensional faults and oblique slip movement on the pre-existing NW-SE suite of compartmental faults. This extensional phase (oriented ca. N-S) involves the re-activation of contractional structures as well as the initiation of new faults which cross-cut the pre-existing features. (Fig. 4.27 and Pl. 4.44). Permian and Tertiary deposits are associated with the brittle faults. The Permian deposits were laid down during initial extension whilst most of the Tertiary deposits have resulted from later re-activation of pre-existing structures. Many of the latter structures have a sinistral sense of displacement. This is shown by the Bovey Tracey Basin which has a pull-apart basin geometry (see Chapter 6) and originates at the same time as the inversion in the Western Approaches Trough (Ziegler, 1987; Hayward & Graham, 1989).

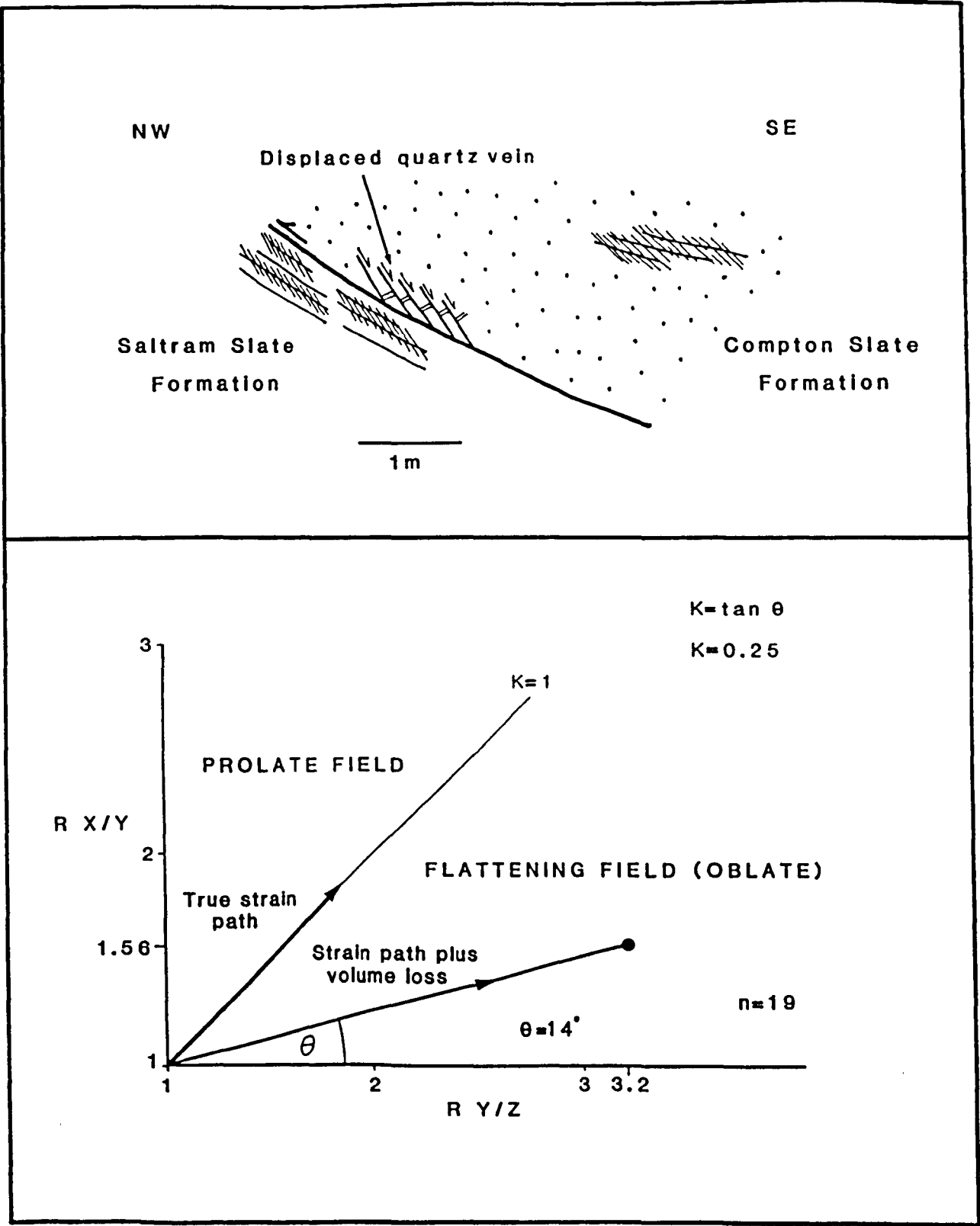


Fig. 4.27 Diagram to show the interaction of late extensional features with a pre-existing Variscan thrust; Warleigh Wood [SX 4490 6120].

Fig. 4.28 Flinn plot produced from reduction spot axes observed in the Dartmouth Group rocks at Heybrook Bay [SX 4965 4870].

Strain

The slates of the Dartmouth Group show apparent flattening strains (Fig. 4.28). Reduction spots (Pl. 4.45) have axial ratios of 1.56:1:0.31 ($n = 19$) with the XY plane being approximately parallel to the cleavage. The deformed spots describe an oblate ellipsoidal shape which may be attributed to volume loss during compaction or tectonic deformation (Ramsay & Wood, 1973). The deformation may well be plane strain with the volume loss producing a result which plots in the oblate field. It is assumed that the reduction spots would have been spherical and hence circular on any of the principal planes of strain in a tectonically undeformed situation. An analogy to this is shown in the Keuper Marl of North Devon near Minehead where this is indeed the case. Here and also in the Dartmouth Group slates there are also irregularly shaped reduction zones which cannot be used for strain analysis.

Slickenside data and the orientation of extension lineations (pyrite growths) are consistent with the strain data obtained from reduction spots in the Dartmouth Group Rocks at Andurn Point [SX 4900 4980] and Heybrook Bay [SX 4970 4875]. The maximum extension direction of the strain ellipsoid (x-axis) in these strain markers trends NW-SE and is parallel to the down-dip lineation on the cleavage in the same rocks.

4.2.2 Large scale structure

Following the examination of the geometry of the small scale (mesoscopic) structures, such as: sedimentary younging directions, vergence and the relationship of cleavage and bedding, it is possible to infer the attitude and style of the larger scale structures. By combining this data with the available stratigraphic and other structural data it is possible to construct large scale cross sections through the southern zone. Four traverses have been examined; West Hams, East Hams, West Sound and North Cornwall. Each of these are divided into sub-areas. A series of cross sections constructed on either side of compartmental faults in order to show how the structures relate are also presented.

West Hams section (Bolt Tail - Cargreen)

Coastal sections between Plymouth and Bolt Tail (see Fig. 2.3) and exposures in the banks along the River Tamar (see Fig. 2.6) reveal Early to Late Devonian age rocks. The

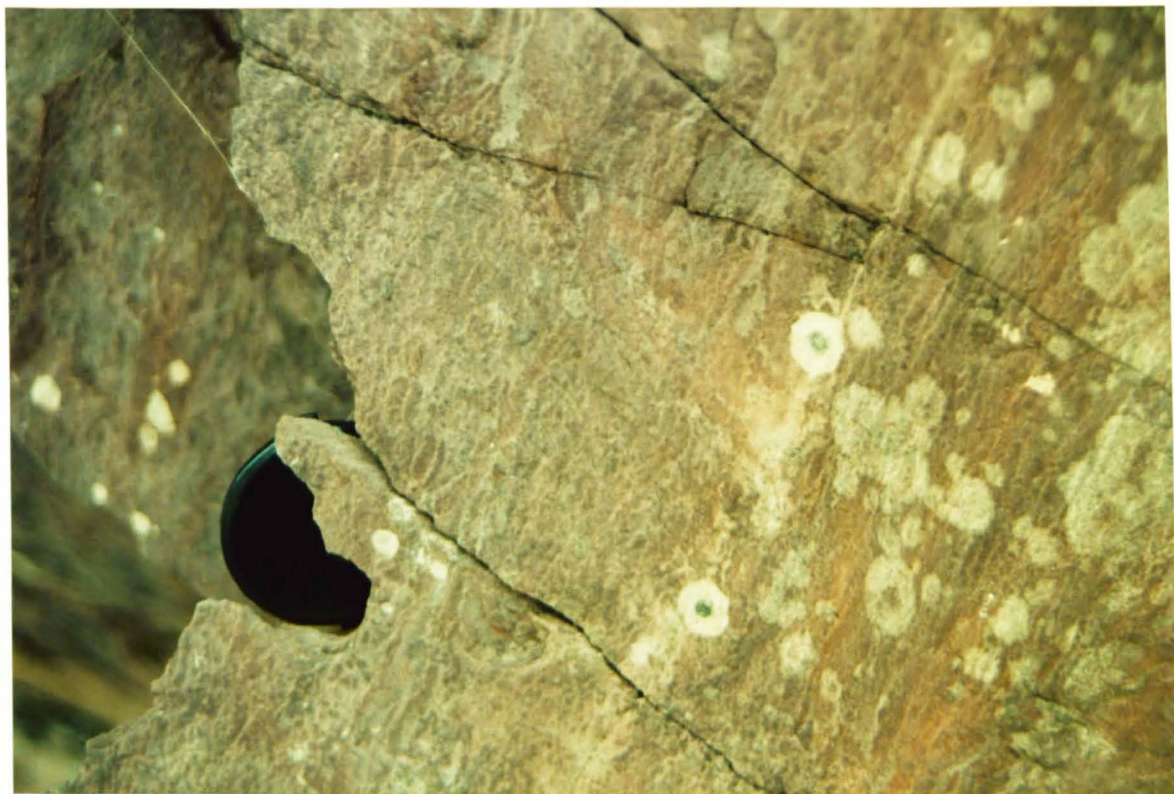


Plate 4.45 Reduction spots within the Wembury Formation at Andurn Point [SX 4920 4975]. Spots are oblate on the first phase cleavage planes. Above rock face is slightly oblique to the cleavage plane.



Plate 4.46 North west facing, first phase fold in the Saltram Slate Formation; Saltram Quarry, Plymouth. Looking north east.

earliest deformation recorded in these areas is represented by D1 folds, thrust faults and cleavage which occur with changing attitude throughout the section. These structural features are described in section 4.2.1. The most distinct feature of the traverse is the gradual steepening of structures from north to south. Fold axial planes and D1 cleavage are gentle to moderately southward dipping in the north but vertical or steeply dipping to the north in the south.

The West Hams coastal section exposes a sequence through the Dartmouth Group rocks. The dominant large scale structure of this section of coastline, previously regarded as the Dartmouth Antiform (Hobson 1976a, b), is now thought to be a fold-thrust structure forming the hanging wall to the Crownhill Thrust (Figs 2.4 and 4.29). This thrust is not exposed due to its displacement at the coast by a NW-SE-trending strike slip compartmental fault, which in turn may have been modified during later extension. Hobson (1976a) deduced that the Dartmouth Antiform was a modified (by D2) D1 fold due to the existence of a consistent change in attitude of the cleavage from north to south. This change in cleavage attitude is real but may have an alternative origin (see section on Wadham Rocks to Bolt Tail).

Cargreen to Plymouth

Structures along this part of the section disrupt a sequence of Middle to Late Devonian age rocks (see Fig. 2.6). In general the stratigraphic distribution of the units mapped vary little from data already published (see BGS sheet nos 348/9; Chandler and McCall, 1985). However, the Plympton Slate Formation (see Section 2.3) has been divided into the Compton Slate Formation and the Saltram Slate Formation allowing more accurate structural mapping and cross section construction to be made. These formations can be examined along the River Tamar and around the city of Plymouth where they are repeated by a series of mesoscopic and macroscopic folds and thrusts. In general the folds are asymmetrical, verge and face towards the NW (Pl. 4.46) and are often thrust related. The cleavage is consistent in its attitude and dips moderately to the SE. Bedding also dips to the SE but due to the folding and thrusting, the resultant sheet dip is sub-horizontal. Another effect of thrusting is to produce a gross younging to the north even though the general bedding dip is southward.

Thrusts mark some of the boundaries between the formations within the Plymouth Group rocks of this area. For instance at Warleigh Wood [SX 6100 4500] and along strike

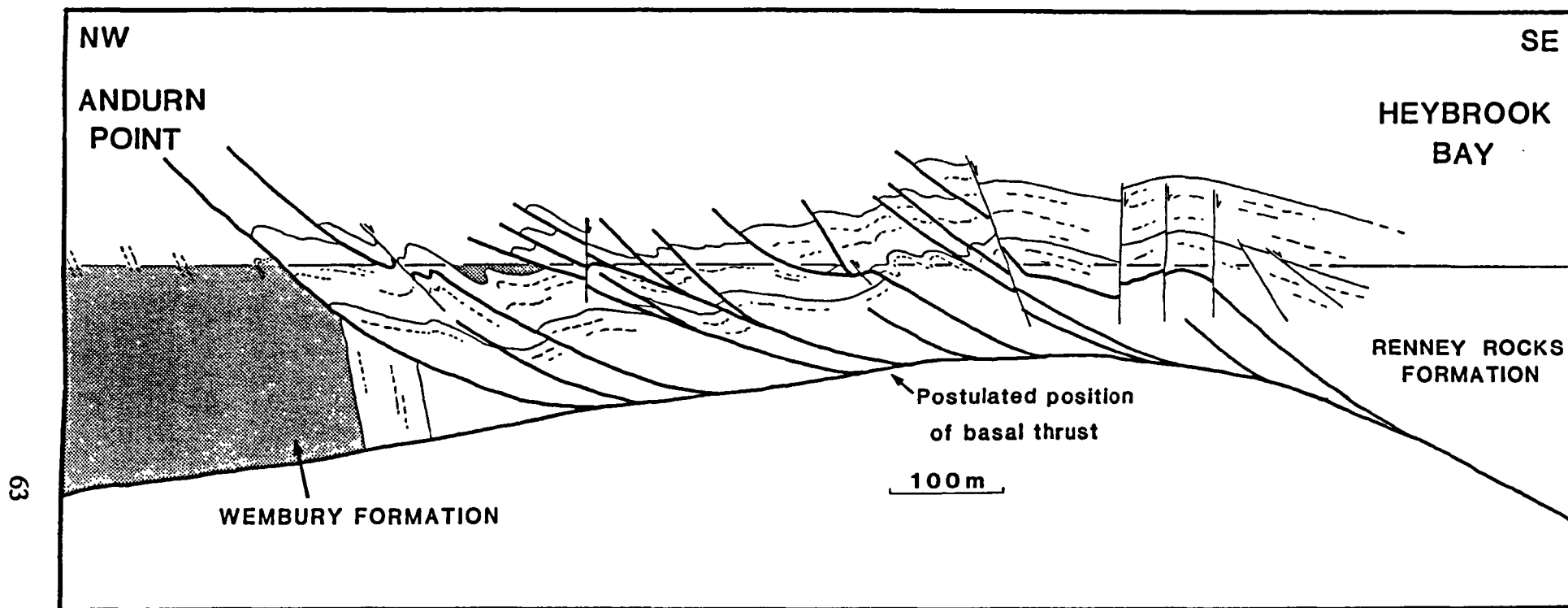


Fig. 4.29 Structural cross section through the Dartmouth Group rocks between Andurn Point and Heybrook Bay.

on the opposite side of the River Tamar between Neal Point and Weir Point, the black slates of the Compton Slate Formation are emplaced over the purple slates of the Saltram Slate Formation. Small scale structures in the hanging wall of this thrust indicate extensional movement, however, the disposition of the stratigraphic units indicate it is still in net contraction and the extension is a later re-activation of the thrust (see Fig. 4.29).

The present outcrop pattern indicates that the erosion level occurs just below and just above the boundary between the Compton Slate Formation and the Saltram Slate Formation along this section. This is a function of an almost flat lying sheet dip. Hence, it seems likely that a flat lying decollement occurs at depth below this region being linked to the thrust system present further to the south (Fig. 4.30). Thrusts which cut the present erosion level probably curve with listric geometry into the decollement at depth (Fig. 4.30). The isolated outcrops of volcanics (tuffs and vesicular pillow lavas), which occur within the Compton Slate Formation (grey and black slate), are a result of folding of volcanic sheets. Bedding/cleavage relationships demonstrate that the volcanic outcrops occur within anticlinal culminations and these may have formed above blind thrusts (Figs 2.6 and 4.30).

Minor folds are observed in many of the slate quarries in and around the city of Plymouth. They are asymmetric, face north, generally have a northward vergence and are common in the slate formations (Fig. 4.31) but rare in the more competent limestones. However, on a larger scale the Plymouth Limestone Formation is folded into a major syncline and is bounded to the north and south by thrusts (Fig. 4.30). Some minor folds and cleavage vergence may be to the north or south depending on which limb of the larger scale folds they are observed.

Plymouth to Wadham Rocks

The geology and localities along this stretch of coastline are illustrated in Figs 2.3, 2.6, 2.8 and 4.29 to 4.32.

In the northern part of this traverse, in the Plymouth city region, the southern end, and base, of the Plymouth Limestone Formation is marked by a sequence of volcanics (Hobson, 1976a; Chandler & McCall, 1985). They are overthrust by the Jennycliff Formation and occupy a major footwall syncline to this thrust. To the north the Plymouth Limestone Formation dips gently south and is thrust over Upper Devonian Slates (the Saltram Slate Formation) (Fig. 4.30). The compartmental fault crossing the mouth of the River Plym terminates at the thrust marking the northerly limit of the Plymouth Limestone Formation.

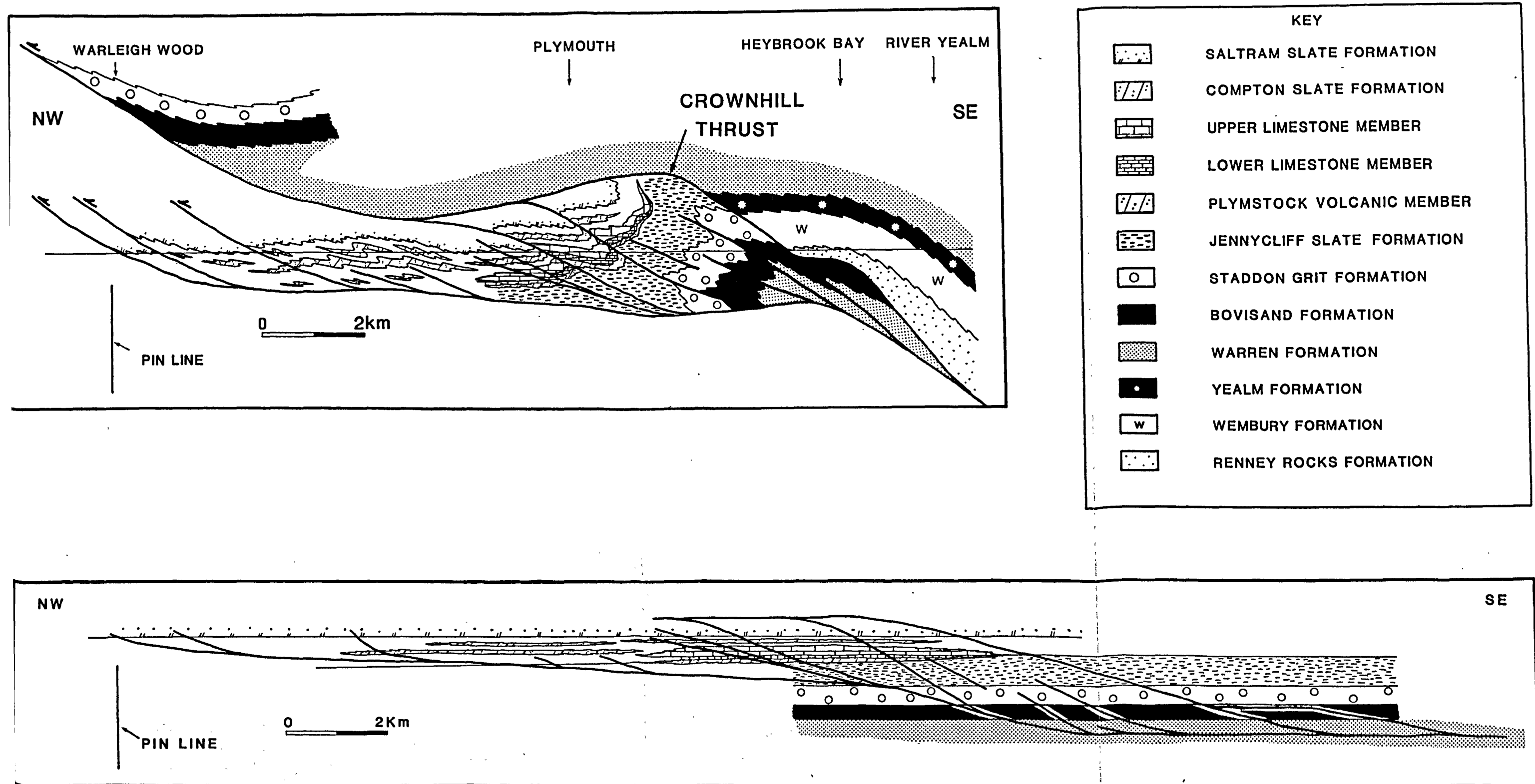


Fig. 4.30 Balanced and restored cross section through the northern part of the southern zone.

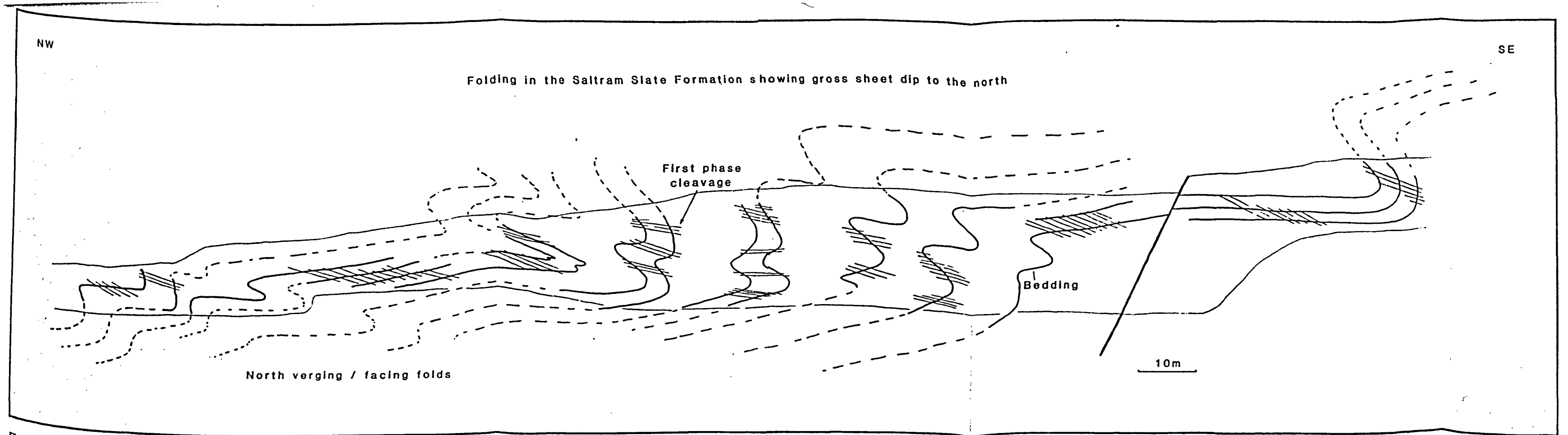


Fig. 4.31 Fold geometries observed in the Saltram Slate Formation in Saltram Quarry, Plymouth [SX 5260 5400].

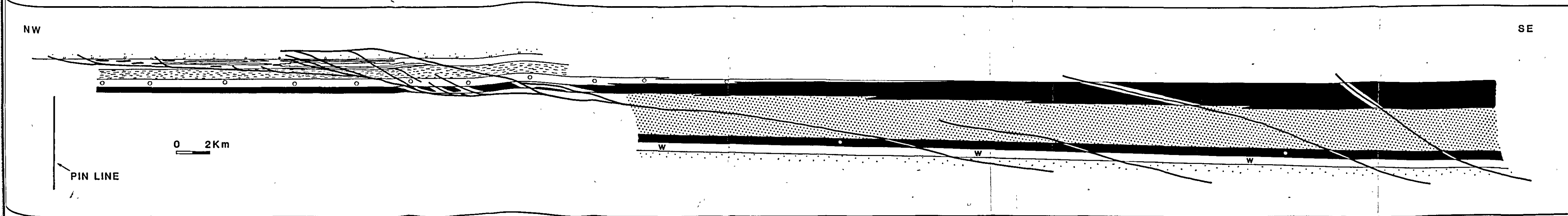
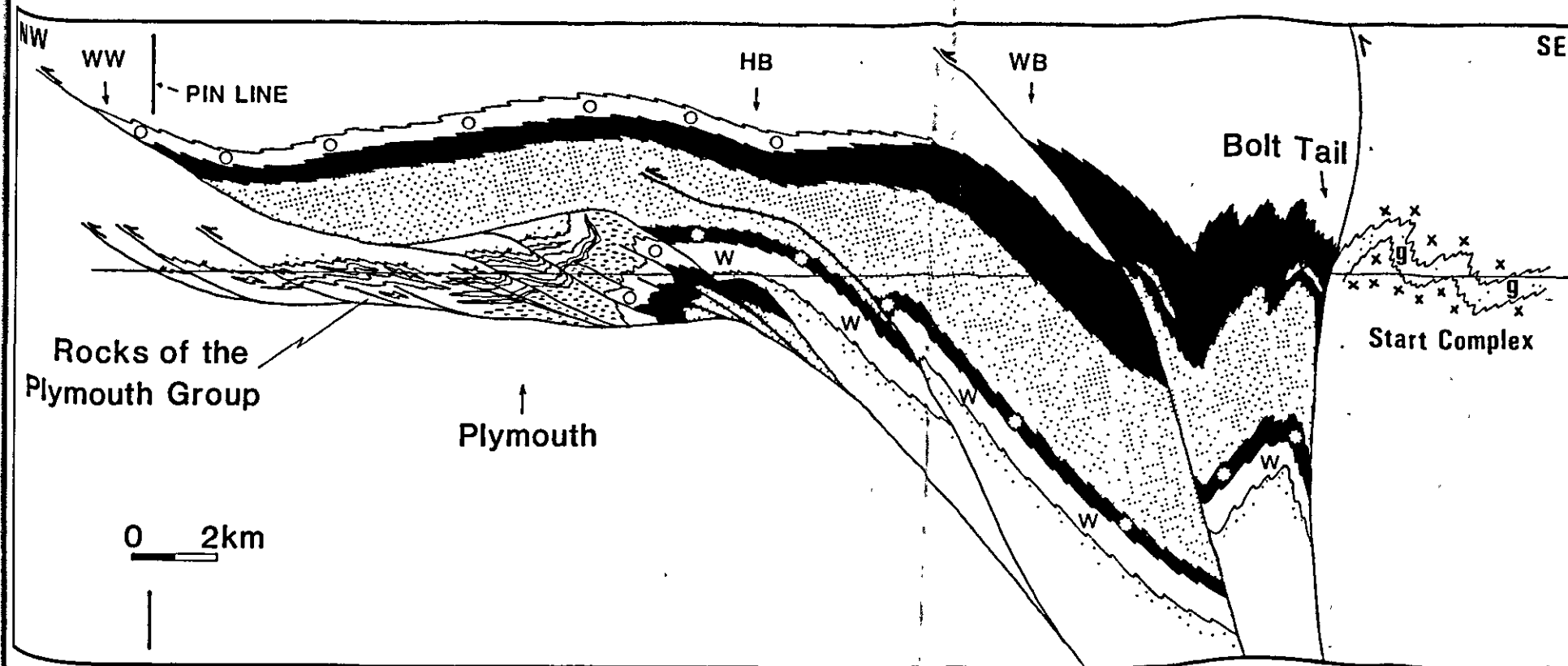


Fig. 4.32 Balanced and restored cross section through the southern zone showing 61% bulk shortening.
 argument to the stratigraphy as Fig. 4.30. x - Quartz mica schists; g - greenschists. HB - Heybrook Bay;
 WB - Westcombe Beach; WW - Warleigh Wood

This suggests that it may join the thrust at depth indicating that they are closely related during their generation.

Further south, at the southern end of Crownhill Bay [SX 4925 4980], in Sandy Cove, the rocks of the Meadfoot Group juxtapose those of the Dartmouth Group (see Fig. 2.8). The contact is interpreted as a vertical fault trending NW-SE from map patterns as the fault plane is not exposed. It is marked by the subtle change in lithology from one side to the other, and by the presence of fossiliferous limestones on the NW side (Meadfoot Group) of the fault. A red bed sequence (probably Permian in age) consisting of conglomerate/breccia is exposed along the proposed position of the fault at the coast. The latter is exposed on the foreshore and along a small inlet where preferential erosion of the fault and the less stable cover deposits has occurred. The red beds are undeformed and the attitude of the crude bedding is sub-horizontal. They invariably lie with angular unconformity on Devonian rocks. Exposures at the back of the beach are now covered by recent land slips. The Permian deposits are similar to those further to the south in the Thurlestone area and to the east in the Torbay area where they are much more extensive.

The fault at Sandy Cove has previously been described as having a component of dip-slip involving 3.7km of displacement (down to the north) (Hobson, 1976a). A more likely origin for this fault is that of strike-slip motion with it belonging to the suite of compartmental faults described throughout the area. The fault can be traced in a south-easterly direction through Wembury to The Warren, a distance of over 4km (Fig. 4.33). The relationships on the foreshore at Wembury [SX 5175 4840] and Cellar Beach [SX 5305 4750] can be examined at low tide. Here the cleavage and bedding curve into, and are displaced by the fault (Pl. 4.47) although this does not define the sense of shear. Shear bands in the fault zone, however, indicate a dextral sense of shear across the fault. In the region of Crownhill Bay (Fig. 4.33) the fault is thought to displace the NE-SW trending contact between the Dartmouth and Meadfoot Group rocks. This contact is interpreted as a thrust (Crownhill Thrust) and although not exposed at the coast, it can be seen to cut across stratigraphy inland. For instance at Whitemoor [SX 6030 4920] (ca. 1.5km SW of Holbeton), it comes into very close contact with the Staddon Grit Formation (see Fig. 4.33).

In Crownhill Bay [SX 4925 4980], south of Plymouth, Lower Devonian (Siegenian to Emsian) clastics are deformed into north verging, north west facing D1 fold-thrust structures (Fig. 4.34 and 4.35, Pl. 4.48). Progressive thrust development towards the foreland has caused refolding of hanging wall structures. This D2 folding of the first phase cleavage results in the formation of steep F2 fold axial planes (Pl. 4.49) and a localised crenulation

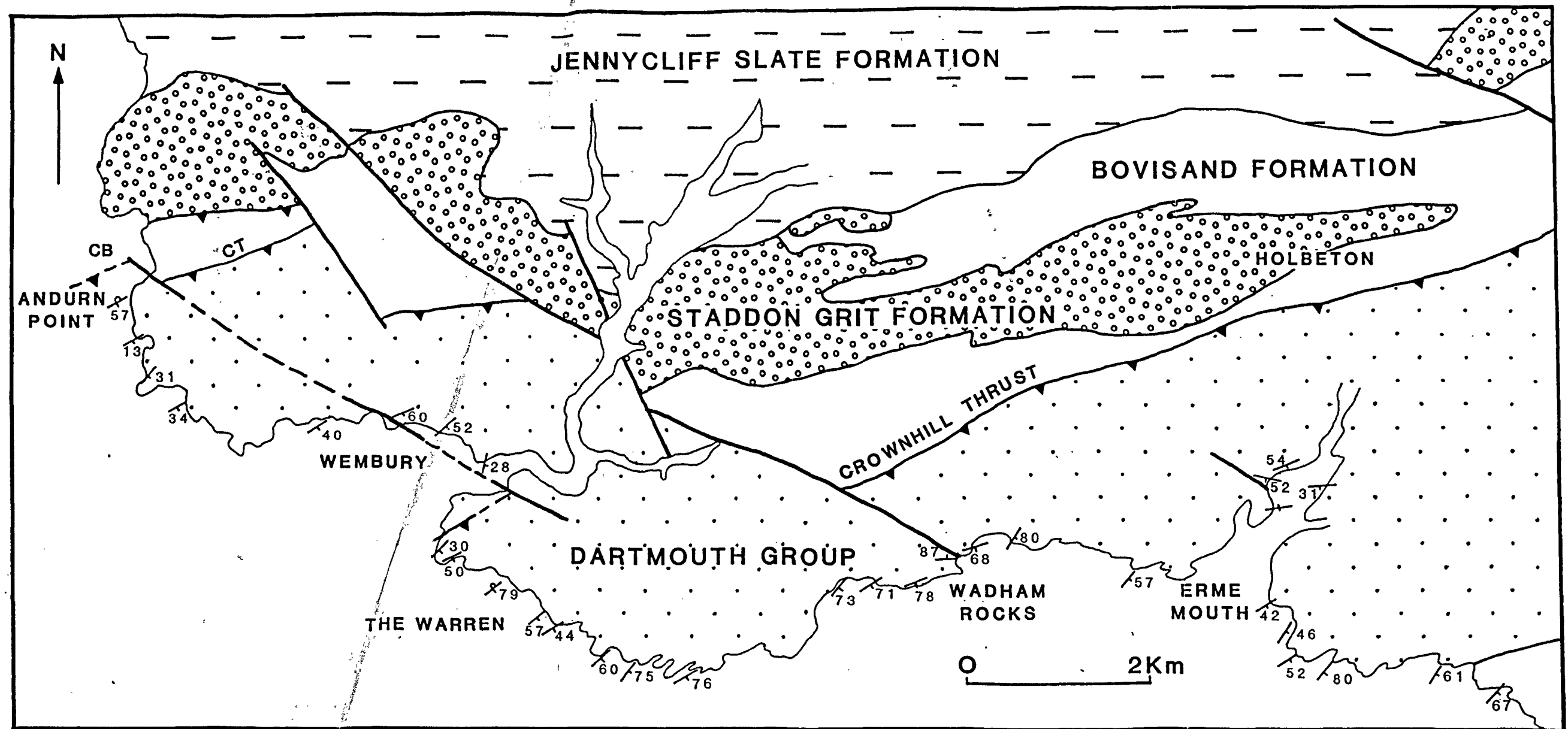


Fig. 4.33 Geological map showing the spatial relationship between the Crownhill Thrust (northern margin of the Dartmouth Group) and the structurally lower Bovisand and Staddon Grit Formations. Inland data obtained from BGS maps. CB - Crownhill Bay; CT - Crownhill Thrust.

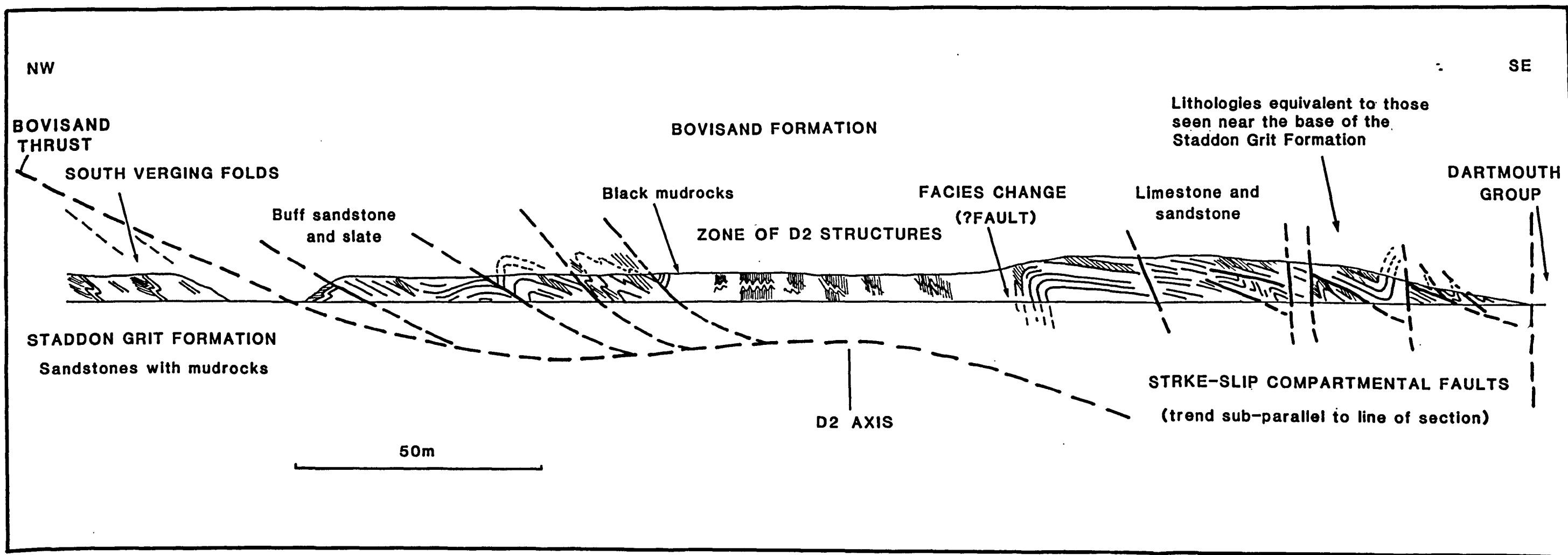


Fig. 4.34 Structural section through the Meadfoot Group rocks of Crownhill Bay [SX 4920 5025].

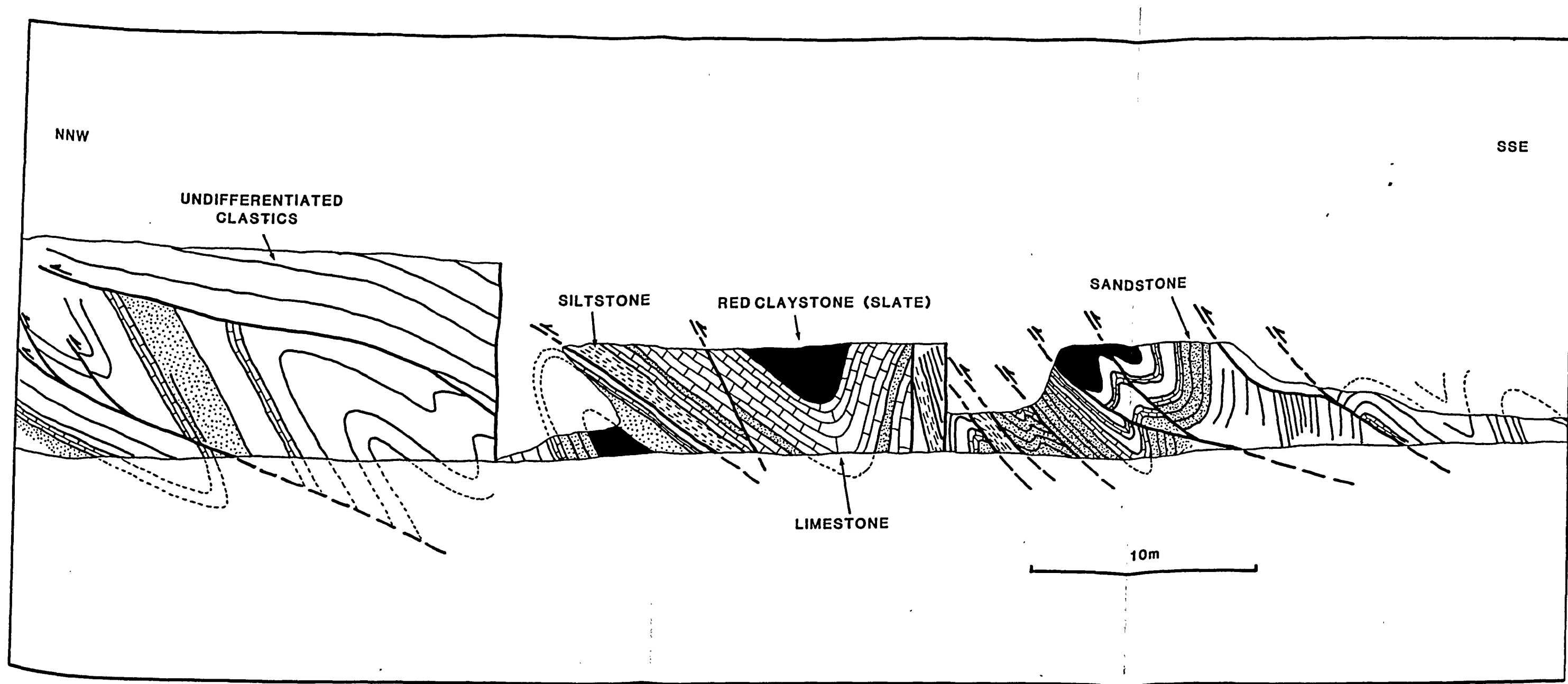


Fig. 4.35 Detailed structural section of the Meadfoot Group rocks of Sandy Cove (south east portion of Fig. 4.34) [SX 4925 4990].



Plate 4.47 NW-SE trending compartmental fault on the foreshore at Wembury Beach [SX 5170 4840]. Note how the bedding and cleavage curve into the fault on the SW side of the fault. Looking west.



Plate 4.48 North west facing structures within the Staddon Grit Formation at Crownhill Bay [SX 4925 4980]. Looking north east. Height of cliff face ca. 12m.



Plate 4.49 Second phase folds and sub-vertical crenulation cleavage in the Bovisand Formation at Crownhill Bay [SX 4925 4980]. Looking north east.

cleavage. This occurs within the core of a broad D2 fold in the hanging wall to the Bovisand Thrust (Fig. 4.35). The thrust emplaces the black pelites of the Bovisand Formation over the coarser clastics of the Staddon Grit Formation. In the hanging wall to this structure the base of the Staddon Grit Formation is also observed (Fig. 4.34). The Bovisand Thrust is covered by superficial deposits but is marked by the break in slope which follows the valley at the back of Bovisand Beach.

North of Bovisand Beach, and in the footwall to the Bovisand Thrust, the Staddon Grit Formation is distributed about a large scale (macroscopic) syncline. The southern, overturned limb of this structure is exposed at Bovisand Beach where small scale parasitic folds verge towards the south (see Pl. 4.50). When traced northwards the beds become sub-horizontal and the right way up. At the southern end of Jennycliff Bay they are folded on the same scale into a major north verging anticline. Throughout this part of the section there are many small scale thrusts and folds (Chapman, 1983). The dip of the strata in the Jennycliff Slate Formation is sub-vertical at the coast and has a relatively small outcrop length. However, inland and on the east side of a NW-SE compartmental fault, they cover a much greater area due to the change in the dip of the strata (now flat lying) (see Fig. 2.6). Clearly deformation styles vary as the structures do not match across the fault indicating that the movement of the compartmental faults was initiated during the Variscan Orogeny.

South of Andurn Point [SX 4900 4980] to as far south as Wadham Rocks the coast displays a continual section through the rocks of the Dartmouth Group, allowing all four of the contained formations to be examined (see Fig. 2.3). The sequence is disrupted by a series of mesoscopic folds (Pl. 4.51) and thrusts and is also dissected by strike slip and late extensional faults. The sheet dip of the section gradually increases from north to south from being sub-horizontal between Andurn Point and just south of Heybrook Bay [SX 4960 4840] to ca. 45°SE at the SE end of the Warren [SX 5540 4575]. A larger scale intra-Dartmouth Group thrust occurs within the Warren Formation in the vicinity of Gara Point [SX 5225 4680] (Pl. 4.52). The displacement along this thrust is difficult to ascertain due to it occurring within one formation.

Wadham Rocks to Bolt Tail

Along this stretch of coastline the Dartmouth Group rocks are deformed into both northward and southward verging folds with moderate to steeply inclined axial planes. The major (macroscopic) folds in the north verge to the north, however, a traverse to the south



Plate 4.50 South east verging, north west facing, first phase folds of bedding in the footwall to the Bovisand Thrust, Staddon Grit Formation; Bovisand Beach [SX 4920 5060]. Looking north east.



Plate 4.51 North west verging mesoscopic fold in the Warren Formation; The Warren [SX 5320 4660]. Looking south west. Width of outcrop ca. 8m.



Plate 4.52 The Gara Thrust with associated hangingwall structures, Warren Formation; Gara Point [SX 5240 4690]. Looking north east.

reveals a zone of folds with neutral vergence where mesoscopic folds verge both north and south. This is followed even further south by a zone of southerly verging folds (see Fig. 4.32).

Three main stratigraphic units occur along this stretch of coastline; the Dartmouth Group between Wadham Rocks and Westcombe Beach, the Meadfoot Group between Westcombe Beach and Hope Cove and the Start Schist complex between Hope Cove and Bolt Tail. The stratigraphic contact between the Dartmouth and Meadfoot Group is exposed at Westcombe Beach [SX 6350 4575] (cf. Dineley, 1966; Hobson, 1976a; and Ussher, 1912). It is purely a lithologic change from red to black pelites although at the contact interfingering of the two rock types occurs. This feature does not appear to be the result of folding as there is no change in the attitude of cleavage and bedding across the zone (see Section 2 for further description of this contact).

Between Westcombe Beach and Hope Cove [SX 6750 3975] a sequence of the Meadfoot Group rocks is exposed. However, at the mouth of the River Avon [SX 6640 4430] there is an inlier of the Warren Formation (Dartmouth Group) (Hobson, 1976a). The presence of a well developed zone of second phase folds and cleavage indicates that the northern margin of this slice of older strata may be thrust-controlled. Balancing and restoration of the cross section requires the thrust to have a displacement of ca. 3km (see Fig. 4.32). At the southern margin of the inlier there is a stratigraphic contact between the Warren Formation and the overlying black pelites of the Meadfoot Group. South of the River Avon, to as far south as Hope Cove, the major folds are more upright and facing of the minor parasitic folds is to the north and south. They are distributed about a major syncline the axis of which occurs between the mouth of the River Avon and Thurlestone Beach (Fig. 4.36). On the northern limb of the fold the bedding is sub-parallel to cleavage but younging is to the south. On the southern limb the beds young and dip north. The fold is crudely defined by the change in attitude of the cleavage which dips south on the northern limb and north on the southern limb. Mesoscopic folds distributed about this major syncline face and verge to the north on the northern limb and south on the southern limb. Structures to the south of this fold record a back steepening phase of deformation.

Many intermediate and minor scale folds are observed between Thurlestone and Hope Cove. South of Thurlestone these folds possess an intense first phase axial planar cleavage (Pls 4.53 and 4.54). This cleavage is locally deformed into D2 folds which possess a steeply dipping crenulation fabric (Pl. 4.55). It is these second phase structures that dominate the traverse towards Hope Cove further south. In the extreme south, adjacent to the Start Fault,

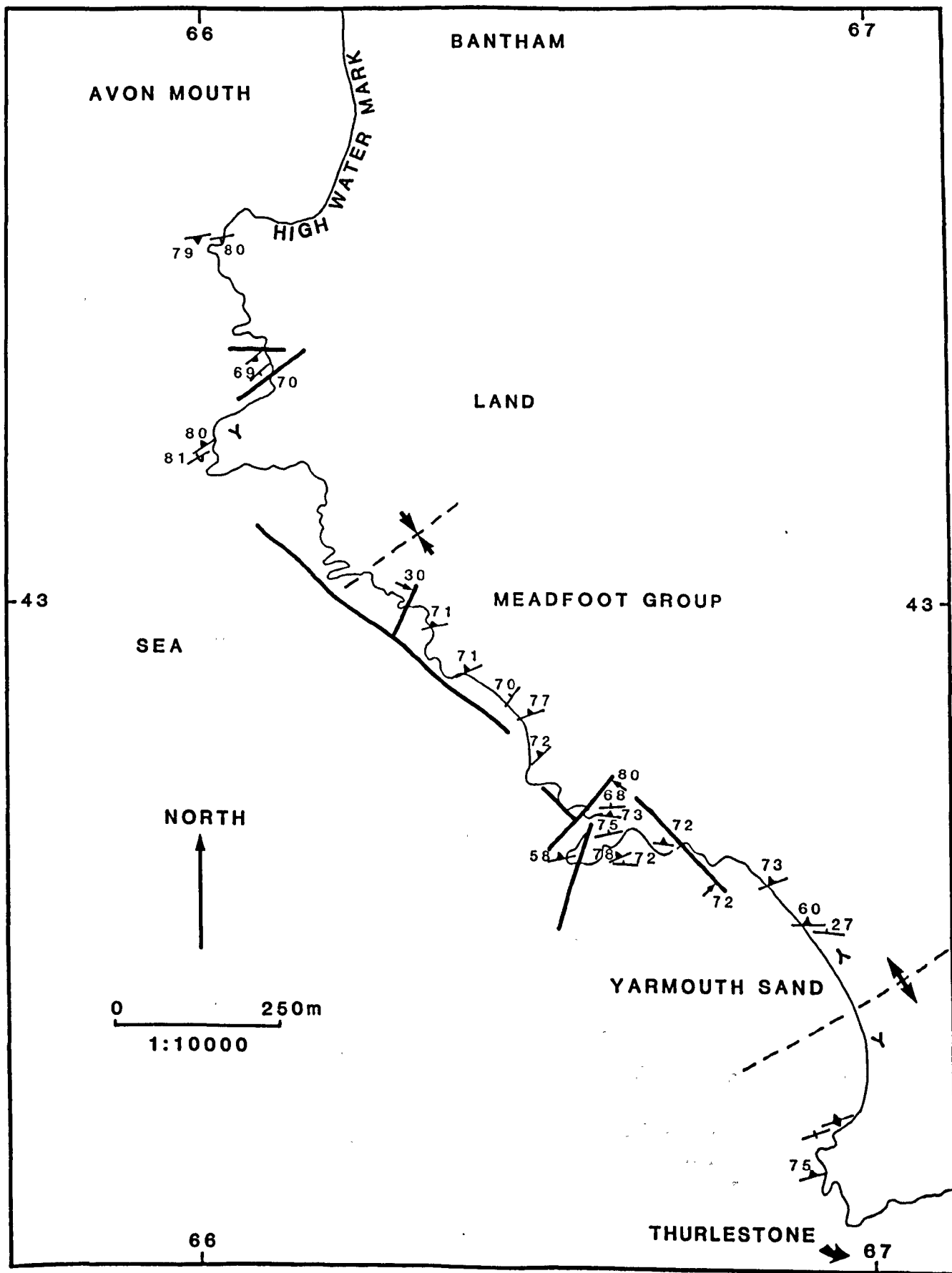


Fig. 4.36 Detailed structural map of the area between Avon Mouth and Thurstlestone.

Plate 4.53 South west plunging, first phase folds and associated axial planar cleavage in the Bovisand Formation exposed at Thurlestone [SX 6745 4195]. Looking south west.



Plate 4.54 Close up of Pl. 4.53.

Plate 4.55 Second phase folds and associated crenulation fabric within the Dartmouth Group rocks of Blackpool Sands [SX 8550 4780]. Looking south west. Pencil nib ca. 2cm long.



Plate 4.56 North dipping faults in the Bovisand Formation near Thurlestone [SX 6745 4195]. Looking east. Height of outcrop ca. 4m.

the folded bedding, although displaying the same geometry as that to the north, is a product of the second phase event and the associated cleavage is a crenulation cleavage. The southern part of this section is also characterized by kink folds (see Pl. 4.37), persistent north dips, and north dipping thrusts (Pls 4.56 and 4.57). These are consistent with a back steepening event.

The junction between the Start Schist Complex and the Meadfoot Group rocks is exposed at Outer Hope [SX 6750 4015] where it is represented by a 75m wide tectonic zone juxtaposing schists and slates. The most deformed part of this zone is adjacent to the schists and is composed of foliated breccias and gouges implying deformation in the upper 12km of the crust above the ductile/brittle transition zone. Shear fabrics indicate dextral movement on an E-W axis (Pl. 4.58). The importance of these and the history and degree of folding across the boundary is reviewed in Chapters 5 and 7.

Estimates of shortening along the West Hams section

The overall geometry of the West Hams section is one of upright, NW facing thrust sheets with no large scale overturning of strata. The cross sections constructed are balanced, restored and examined for bulk shortening. Balancing and restoring the cross sections is complicated due to the presence of a series of section parallel compartmental faults. The nature of these faults is not conducive to balancing techniques as deformation can vary between each compartment (see previous section). Also, due to the majority of data being limited to coastal outcrops it is not possible to obtain structural observations from one compartment alone for the entire length of the cross section. Hence, in order to allow the cross section to be continuous stratigraphic contacts are matched between one compartment and another. This does not overcome the problem but gives the most reasonable estimate on shortening amounts. The cross sections are regarded as partial restorations as the thrust sheets are internally balanced only, due to the lack of an undeformed foreland. The lack of an undeformed foreland, the limited coastal outcrops and the numerous lateral changes in facies of the rocks present problems in constructing a stratigraphic template of the undeformed strata. This has therefore been derived during construction of the deformed state cross section. The present position of the coastline allows data for the sections to be collected along a direction parallel to the transport direction. This overcomes problems when cross sections are drawn oblique to the general movement direction. Even though the area is not ideal for constructing balanced and restored cross sections the process is still felt worthwhile in order



Plate 4.57 North dipping fault with intense folding in the fault zone within the Dartmouth Group rocks of Compass Cove [SX 8845 4930]; south of Dartmouth. Looking west. Field of view (width) ca. 1m.

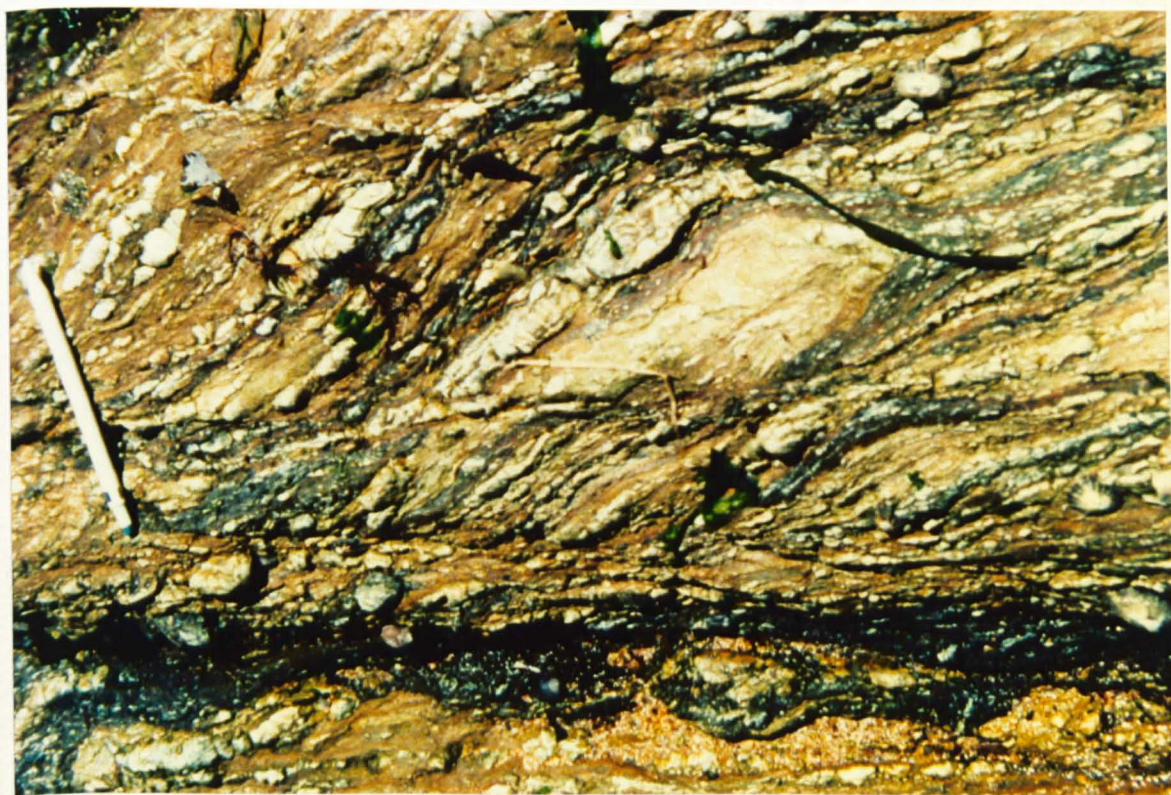


Plate 4.58 Shear zones in the foliated breccias along the Start Fault. Shear bands are oriented E-W and indicate dextral motion; Hope Cove [SX 6750 3980].

to produce the most likely deformed state cross section.

The section through the northern part of the southern zone is shown in Fig. 4.30. The resulting undeformed section shows that 37.5% bulk shortening has occurred during deformation. However, this value would increase if the effects of cleavage formation was accounted for. The complete section through the southern zone has also been balanced and restored (Fig. 4.32) and indicates that bulk shortening is 61%. This value includes an estimate of the internal strain (ca. 30%) by taking into account the effects of minor folds and cleavage formation. This value is a minimum as it usually indicates the onset of cleavage formation. However, a value of 70% as indicated by the limited strain data collected at one locality is considered to be too high as a general value for the area. Thus 61% shortening obtained from the cross section should be considered as a minimum value.

East Hams section (Start Point - Torbay)

Coastal exposures between Hallsands in the south and Berry Head in the north (Figs 4.37 and 4.38) have been examined in order to compare the structure with that of the West Hams coast. The rock units present along this part of the East Hams coast are of Early to Middle Devonian age and are continuous along strike with those described in West Hams. Hence the stratigraphic terms used in West Hams are generally applicable here. For this reason detailed stratigraphic analysis has not been carried out on the rocks of the East Hams section.

Berry Head to Dartmouth

Middle Devonian limestones are exposed to the north and south of St. Mary's Bay which in turn contains a sequence of Middle Devonian slates (Fig. 4.37). The limestones at the southern end of St. Mary's Bay are folded into an F1 inclined syncline which faces to the north (see Fig. 4.39). The orientation of the northern limb of the fold is $097^{\circ}/58^{\circ}\text{S}$ and is the right way up. The southern limb is overturned and bedding is parallel to the cleavage ($101^{\circ}/64^{\circ}\text{S}$). These limestones are thrust over the slates and sandstones which are exposed in St. Mary's Bay. This thrust is folded into an anticline and crops out at the south and north ends of the beach. Overturned strata exposed in St. Mary's Bay (Pl. 4.59) therefore occur in the footwall to this thrust. The structures are complex in this area and numerous lateral ramp geometries are observed (Fig. 4.40). Slip vectors indicate NW transport ($02^{\circ}/306^{\circ}$) and are

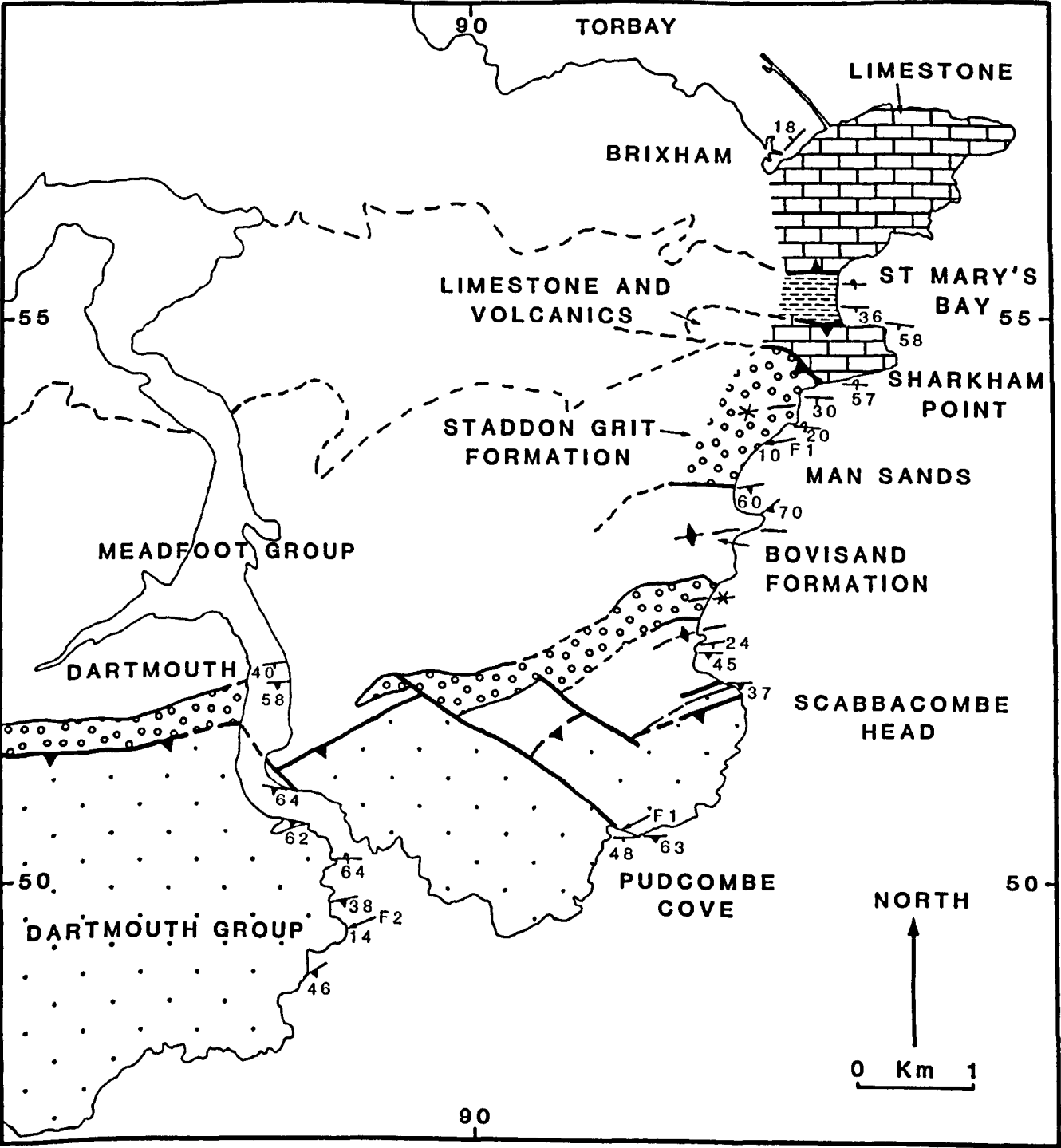


Fig. 4.37 Geological map of the area between Brixham and Dartmouth.

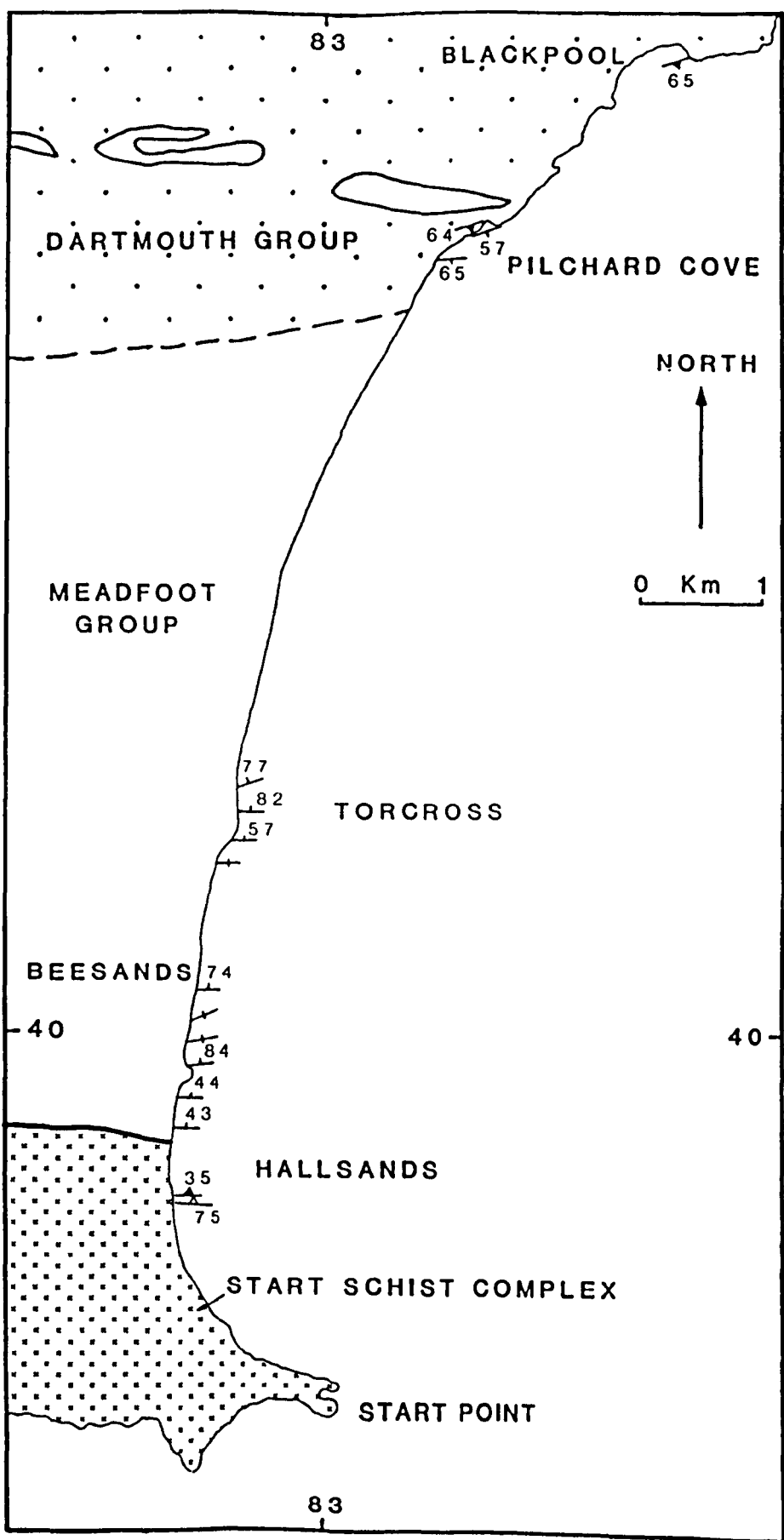


Fig. 4.38 Geological map of the area between Blackpool Sands and Hallsands.

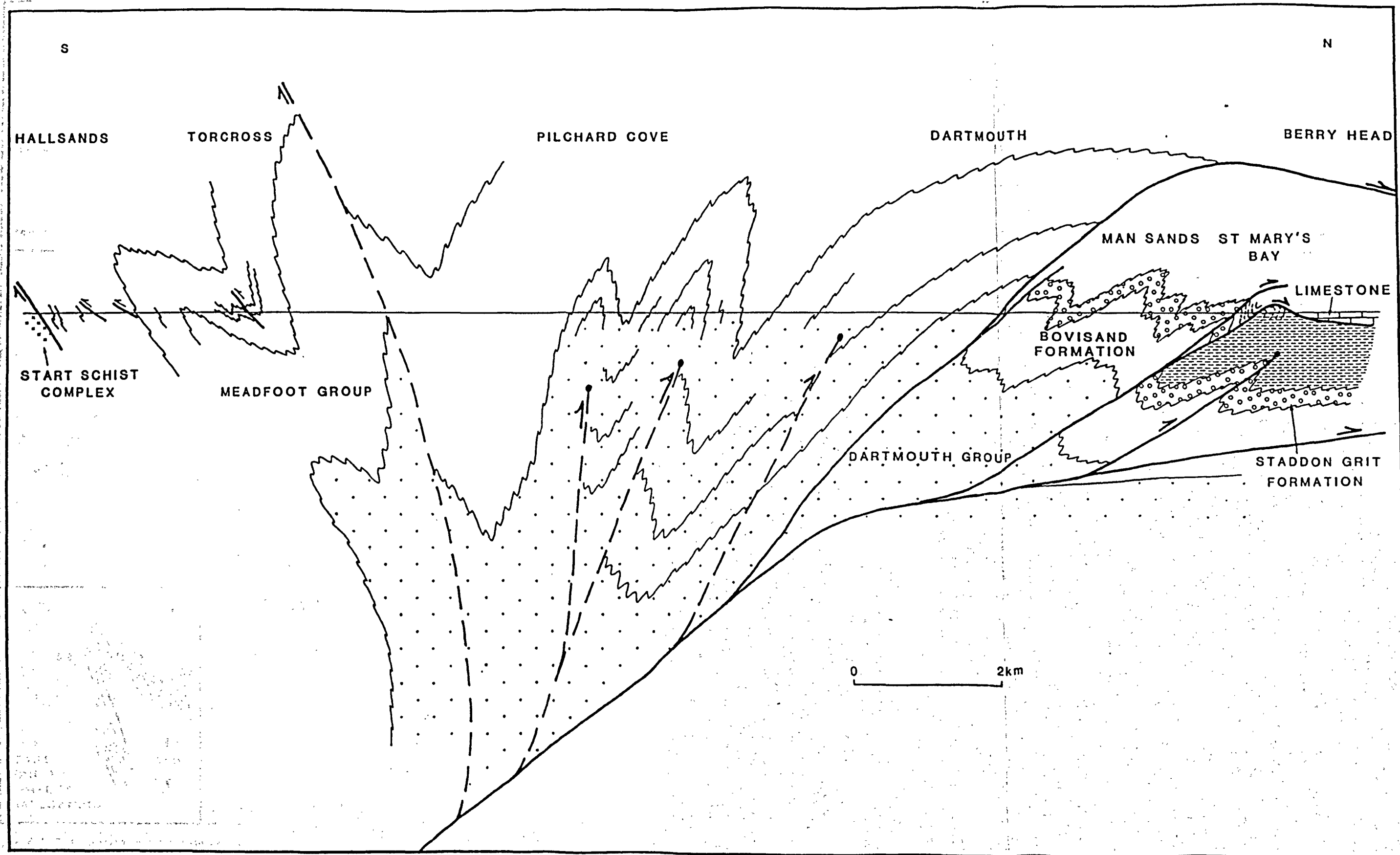


Fig. 4.39 Semi-schematic structural cross section constructed from the data collected along the coast between Brixham and Hallsands. Note that the coast trends NE-SW whilst the profile trends N-S.

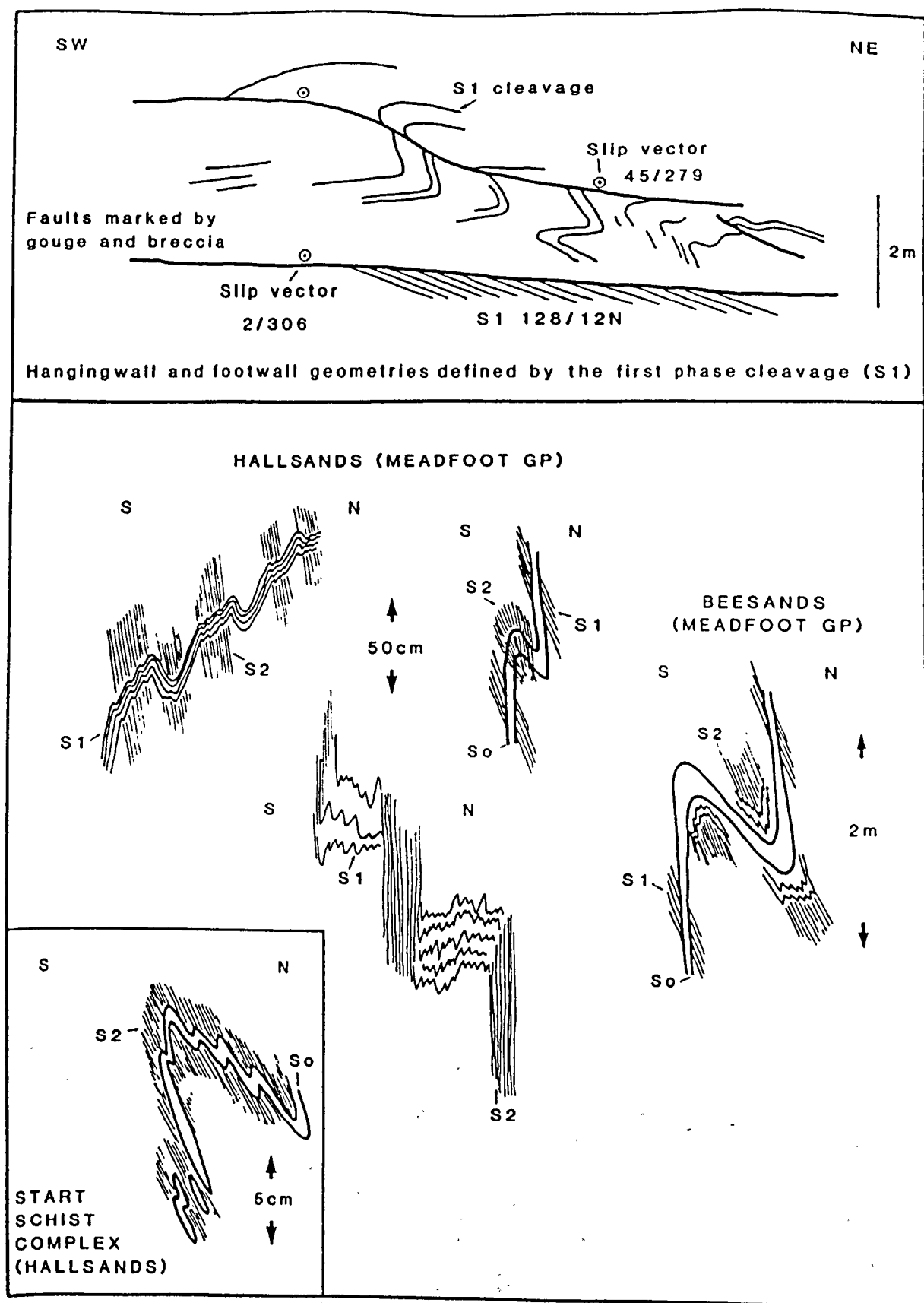


Fig. 4.40 Lateral ramp geometries observed at St. Mary's Bay [SX 9320 5540] in the equivalent unit of the Jennycliff Slate Formation of West Hams.

Fig. 4.41 Bedding/cleavage relationships in the Meadfoot Group rocks to the north of the Start Fault [SX 8175 3925] and in the Start Schists to the south of the Start Fault [SX 8175 3875].

Plate 4.59 South verging, minor scale, first phase fold in the slates of St. Mary's Bay [SX 9320 5520]. The sequence is overturned and facing is northwards. Looking west. (compare with Pl. 2.7).



Plate 4.60 South verging, north facing, mesoscopic, first phase fold on the northern, inverted limb of the Man Sands Anticline. Staddon Grit Formation; Man Sands [SX 9240 5380]. Looking west.

parallel to hanging wall fold axes.

A thrust contact is also present just to the south of Sharkham Point and it separates Middle Devonian limestones and volcanics from the Lower Devonian succession which in turn crops out further to the south. At Man Sands the latter are distributed about macroscopic F1 folds which verge and face northwards. However, mesoscopic folds verge both north and south (see Pl. 4.60 and Fig. 4.39). Mapping in this area has shown that a reddened coarse sedimentary facies overlies a dominantly black pelitic facies. This is indicated by the relative distribution on the structural profile (Fig. 4.39). This relationship applies to this particular thrust sheet but may not be the case elsewhere where a more complex sedimentary relationship involving interfingering of the two units may occur. This is indeed the case at Long Sands where the coarse facies dips beneath the black pelites. The coarse and fine facies exposed in this area are hereafter termed the Staddon Grit Formation and the Bovisand Formation respectively and form the Meadfoot Group as defined in the West Hams area. Along this section the Lower Devonian sequence is repeated by minor thrust faults at Long Sands and Scabbacombe Beach.

At Scabbacombe Head the rocks of the Dartmouth Group crop out and extend to the south towards Dartmouth and beyond (see following sections). The overall structure of the Scabbacombe to Dartmouth section is one of north verging and facing folds (F1 and F2). Thrusts generally show displacements to the north although backthrusts are present with southward directed movements. The contact at Scabbacombe Head between the Dartmouth Group and Meadfoot Group is stratigraphic. Dips are consistent to the south (090°/37°S) with the Meadfoot Group rocks dipping beneath those of the Dartmouth Group, a function of overturning (Fig. 4.37). Inland at Broomhill [SX 8470 5060] the contact between the Dartmouth Group and the Meadfoot Group becomes a thrust and the Dartmouth Group is thrust over the Staddon Grit Formation with a significant displacement. It is likely therefore that a major thrust exists at the coast but within the Dartmouth Group (Fig. 4.37). Thrusts are observed just south of the stratigraphic contact within the Dartmouth Group and indicate northward transport although backthrust geometries indicated by kink bands with southward directed movement also occur. Slip vectors are oriented 06°/162°, kink band fold axes are oriented 11°/262° and thrust planes are oriented 104°/24°S.

Further south at Pudcombe Cove the Dartmouth Group rocks are disrupted by many steep faults similar to the compartmental faults observed in West Hams. One of these faults trends NW-SE through the Bay but subsidiary faults trend 018°. Slickensides on these faults trend 12°/002°. Bedding and cleavage generally dip SE although folding produces occasional

NW dips. As in West Hams the F2 folds are co-axial with the F1 folds the former having fold axes oriented NE-SW (eg. $16^{\circ}/259^{\circ}$).

Around the coast to the south, the Dart Estuary provides a cross-strike section through the Dartmouth Group rocks equivalent to the coastal section south of Scabbacombe Head (see Fig. 4.37). Both Dartmouth and Meadfoot Group rocks occur but the boundary is not exposed. However, dip data suggests that the Dartmouth Group is thrust over the Meadfoot Group (Fig. 4.37). To the north of this contact the Meadfoot Group is the right way up and cleavage is steeper than bedding. The presence of much faulting in the Dartmouth Group rocks immediately south of the contact at Kington village [SX 8850 5080], and the overall southerly dip to the Dartmouth Group sequence, suggests major thrusting at the contact. The overall structure within the Dartmouth Group sequence resembles that along strike to the east, at the coast, where generally SW dipping bedding and cleavage is locally disrupted by folds and thrusts. F2 folds and associated crenulation cleavages are also common. Many of these F2 folds and cleavages are directly associated to thrust faults, indicated by their absence from the thrust footwalls (see Fig. 4.7). The same mode of formation applies to similar structures described in the West Hams section.

Dartmouth to Slapton Sands

Between Dartmouth and Slapton Sands the rocks of the Dartmouth Group are folded into north facing folds which display sub-vertical axial planes. The cleavages associated with these structures are also very steep. Younging directions are generally to the south or south east. The cleavage (S1) is folded into north verging micro-folds by small scale F2 structures (see Pl. 4.55) and these are co-axial to the F1 folds. These features are well displayed at Blackpool Sands [SX 8550 4785]. In general the dip of the S1 cleavage steepens from north to south from ca. $081^{\circ}/40^{\circ}\text{S}$ in the Dart Estuary to ca. $085^{\circ}/75^{\circ}\text{S}$ at Pilchard Cove [SX 8430 4650], at the north end of Slapton Sands (see Figs 4.37 and 4.38). These relationships indicate that there is a general steepening of primary structures from north to south. The southernmost exposures of the Dartmouth Group are observed at Pilchard Cove and further south the rocks are covered by the Recent deposits of Slapton Sands.

Slapton Sands to Hallsands

Much of this section is unexposed, however, two areas have good outcrop. These

occur at Torcross and the Beesands to Hallsands section where rocks of the Meadfoot Group and Start Schist Complex are exposed. The boundary between the Dartmouth Group rocks exposed to the north of Slapton Sands and the Meadfoot Group rocks is buried beneath Recent deposits. However, it has been mapped inland (BGS sheet no. 356) and it is assumed to be a stratigraphic contact similar to that observed in the West Hams area. Between Torcross and the north end of Beesands Beach the rocks of the Meadfoot Group are deformed by a number of mesoscopic folds. These are distributed about a larger macroscopic structure (anticline/syncline pair) which appears to be north verging (Fig. 4.39). Fold axial planes are in general steeply dipping to the north. Minor F2 folds deform this cleavage and have an associated axial planar crenulation cleavage (S2). The general attitude of S2 is ca. 45°N. A number of north dipping faults in these sections indicates movement towards the south. Hence the structure at Torcross is believed to be controlled by a north verging anticline/syncline fold pair which has been steepened during thrust stacking and southerly directed folding with the latter forming as accommodation structures during back steepening.

At the southern end of Beesands there is almost continuous outcrop to the village of Hallsands where the Start Schist Complex is exposed (Fig. 4.37). In this section the S2 cleavage and F2 folds become more prominent and the S1 cleavage is invariably folded. The resulting S2 cleavage dips shallowly towards the north (092°/25N°) but is usually confined to the hinges of the F1 folds (Fig. 4.41). Younging is towards the south as indicated by grading and cleavage refraction in the sandstone units. F2 folds of bedding occur and their geometry resembles that of the F1 folds. The S1 cleavage is folded around the hinges of some of these folds and an axial planar S2 cleavage cross cuts the bedding and the S1 cleavage in the hinge zone. The overall structure of the section north of Hallsands is one of north verging mesoscopic F2 folds of S1 cleavage. Little can be said of the primary structure due to the lack of bedding in certain parts of the section.

At the north end of Hallsands beach (Greenstraight) the Meadfoot Group rocks juxtapose those of the Start Schist Complex. The junction is marked by a series of faults with associated fault breccias. The present attitude and nature of the faults imply that they have normal displacements but may have overprinted the original nature of the boundary. To the south of the contact zone the Start Schist Complex consists of micaceous and amphibolite schists of a higher metamorphic grade than the slates of the adjacent Meadfoot Group but structures present in the two rock units can be correlated across the boundary (see Chapter 5). At the southern end of Hallsands Beach small scale folds (F2) (Pl. 4.61 and Fig. 4.39) refold an S1 cleavage.

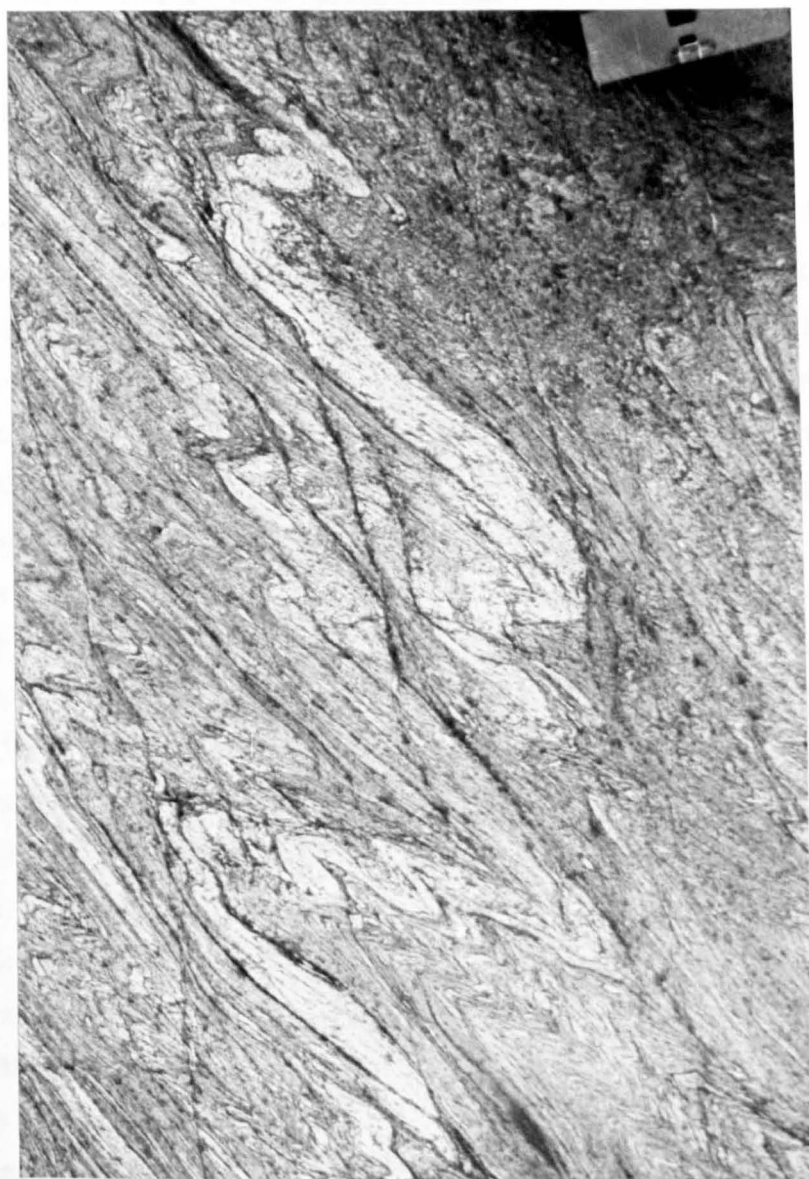


Plate 4.61 Second phase folds in the Start Schist Complex at Hallsands [SX 3875 8180]. Looking west.

The structures described above are consistent with the back steepening model presented for the equivalent sections in the West Hams area (Wadham Rocks to Bolt Tail). The localised nature of the S2 cleavage in fold hinges is thought to be a product of hinge tightening of F1 folds during this back-steepening event.

West Sound section (Rame Head - Plymouth)

The structural and stratigraphic relationships of the Palaeozoic rocks within the area on the west side of Plymouth Sound is investigated in order to compare with that of the West Hams section (see Figs 4.42, 4.43 and 4.44). Structures are consistent with those observed elsewhere in the southern zone and an Early to Late Devonian sequence is present. New Red Sandstone rocks also occur and unconformably overlie the Devonian sequence. The data collected from the coastal exposures are combined with published data and existing BGS maps in order to evaluate the regional structure.

At Rame Head, the southern limit to this section, a faulted outlier of black/grey pelites and thin psammites (Bovisand Formation of the Meadfoot Group) occurs and is sandwiched between red/purple and green slates of the Dartmouth Group (undifferentiated in this section). Cleavage and bedding are steeply inclined to the south in both rock units and the fault contacts are assumed to be sub-vertical. Bedding ($085^{\circ}/75^{\circ}\text{S}$) is steeper than cleavage ($085^{\circ}/66^{\circ}\text{S}$) in the Bovisand Formation indicating a possible position on an inverted fold limb to an overriding thrust. Between Rame Head and Penlee Point the coast swings parallel to strike and the Dartmouth Group is exposed. At Penlee Point green slates of the Dartmouth Group display sub-vertical bedding and cleavage ($092^{\circ}/85^{\circ}\text{S}$). Beds are boudinaged with long axes oriented $00^{\circ}/092^{\circ}$ and the boudins are separated by quartz fills (Pl. 4.62). The steep attitude to the Dartmouth Beds continues northwards along the coast to Kingsand where red slates are observed. Here the bedding and cleavage are also steeply inclined and parallel ($105^{\circ}/85^{\circ}\text{N}$). Numerous sub-vertical E-W trending faults are observed along the coast between Penlee Point and Kingsand but detailed work is hampered by difficulty of access.

At Kingsand, and for approximately 800m to the north, there is an extensive outcrop of Upper Palaeozoic felsite. This is heavily weathered, red in colour, coarsely crystalline with phenocrysts of quartz and feldspar set in a fine matrix. The exposure exhibits a sub-horizontal layering and has been mapped inland over an area of 0.5km^2 (see BGS sheet no. 348). A large NW-SE fault occurs at Kingsand and juxtaposes this felsite with the Dartmouth Group

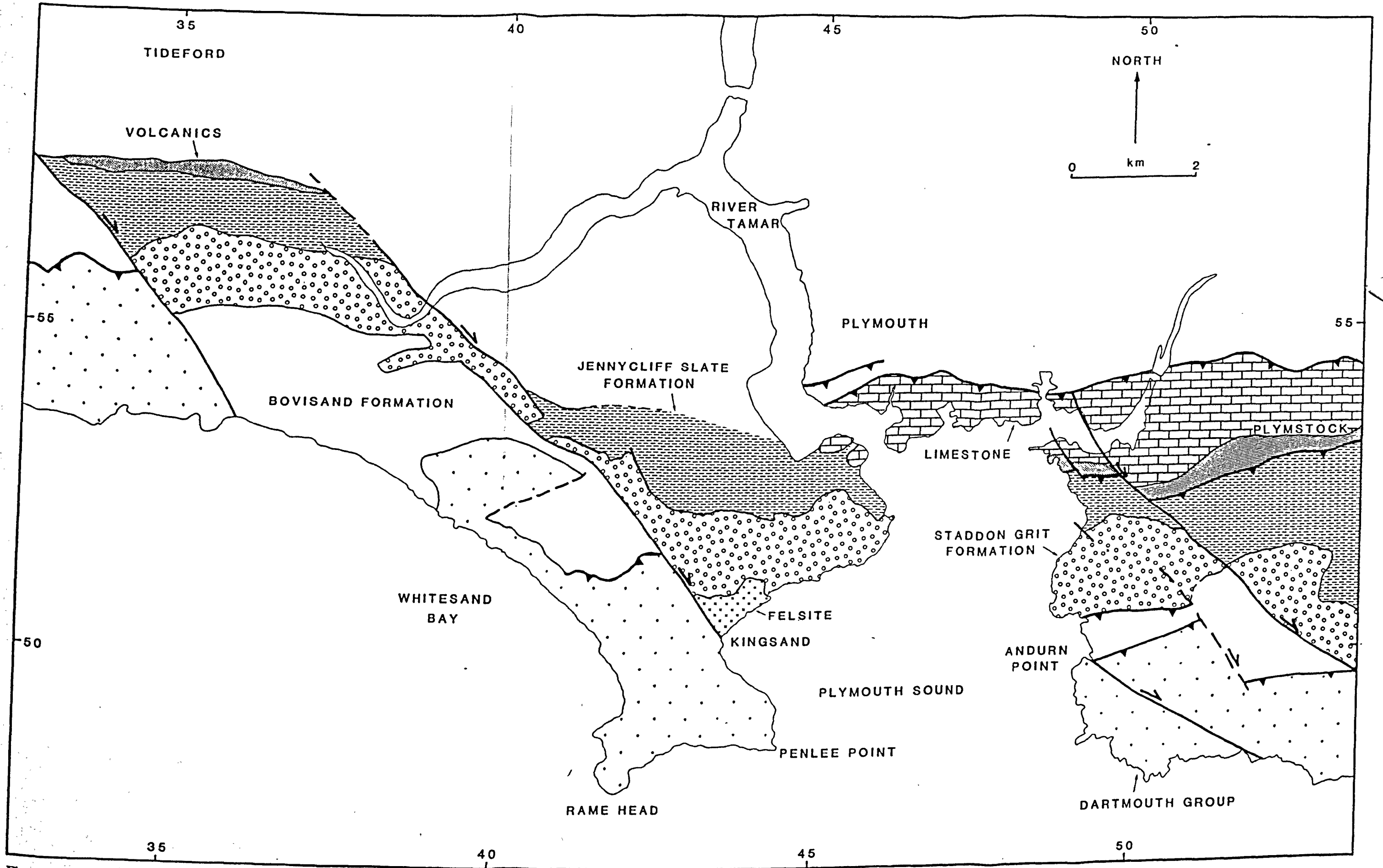


Fig. 4.42 Geological map of the area to the west and east of Plymouth Sound. Data compiled from BGS maps and this study.

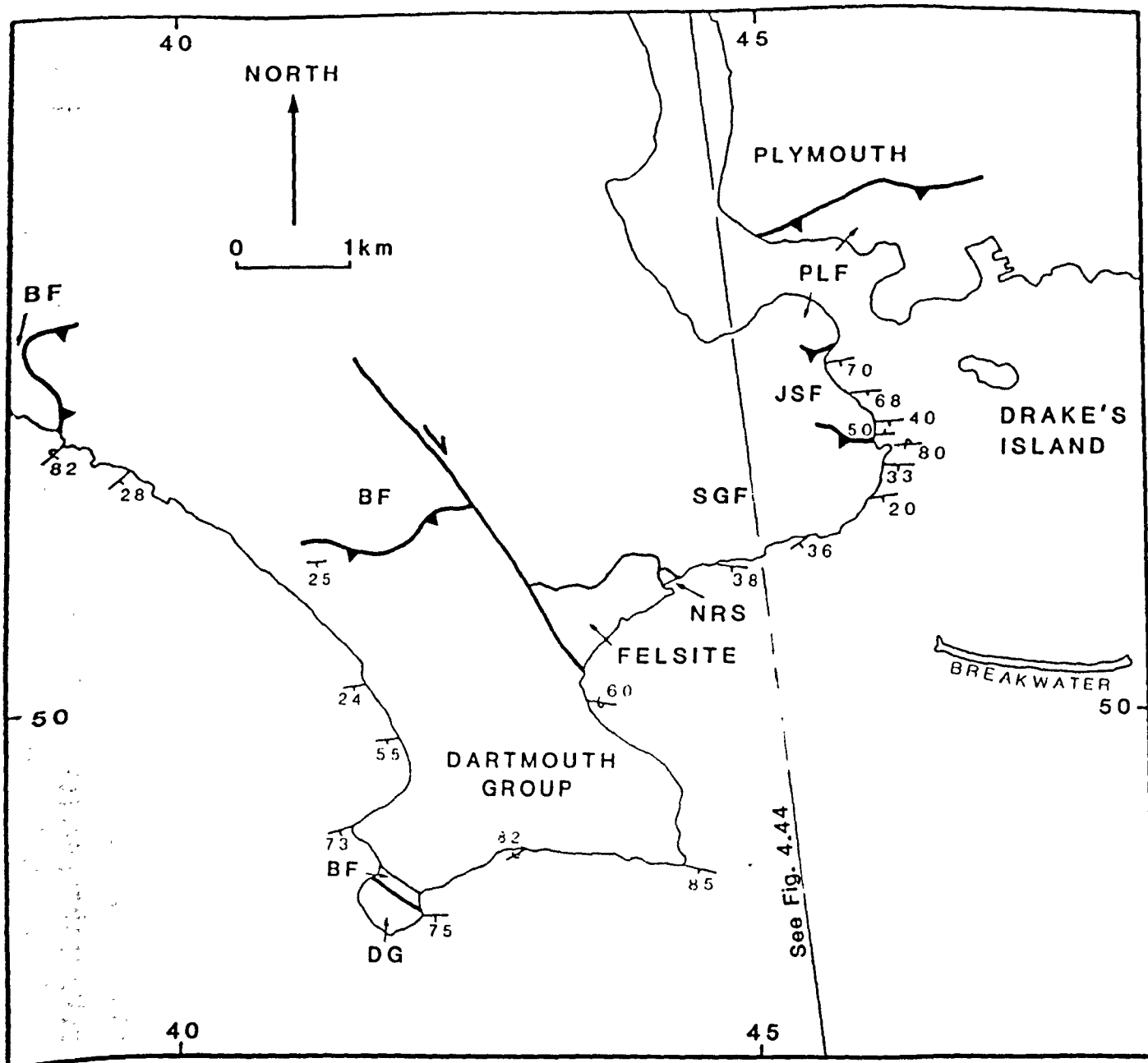


Fig. 4.43 Structural map of the area to the west of Plymouth Sound.

Fig. 4.44 Cross section along the west side of Plymouth Sound.

rocks to the south (see BGS sheet no. 348). This fault is part of the suite of NW-SE faults mapped across SW England. Further inland of Kingsand the fault juxtaposes Dartmouth Group rocks with those of the Staddon Formation (Meadfoot Group) (see BGS sheet no. 348). The importance of the Kingsand fault is addressed below.

A minor outcrop of breccia/conglomerate occurs at the northern limit of the felsite and displays sub-horizontal bedding (5° to 10° S). It contains clasts which range in size from 2-50cm composed of felsite, slate, sandstone and limestone set in a sandy matrix of similar composition. This unit (New Red Sandstone) unconformably overlies a deformed clastic sequence to the north. This clastic sequence is exposed along an oblique section to strike as far north as a small promontory known as The Bridge [SX 4605 5220]. In this section the clastics (Staddon Grit Formation) is composed of interbedded sandstones and claystones, the former often metres in thickness. It is deformed into numerous E-W trending folds which generally plunge gently to the west and are occasionally cut by thrusts. Vergence is to the north with the folds having long, gentle, south dipping southern limbs and short, overturned, vertical or north dipping northern limbs. Folds face northwards and upwards. Sub-vertical, cleaved, doleritic dykes are common and invariably trend N-S. At The Bridge the Staddon Grit Formation is thrust over a sequence of grey/black slates with interbedded sandstones, limestones and volcanics (Jennycliff Slate Formation). The frequency of folding is similar to that observed in the underlying Staddon Grit Formation and strikes are consistently E-W. Dips are generally of the order of 40° to 60° and in general the vergence and facing is the same as that observed in the Staddon Grit Formation. The Jennycliff Slate Formation is continuous in outcrop to the north end of Barn Pool [SX 4555 5305]. Here it is thrust over limestones which are laterally continuous with the Plymouth Limestone Formation exposed in the Plymouth Hoe region.

The above data are consistent with data collected elsewhere in the study area. The one striking dissimilarity is the apparent rapid transition southwards to steeply inclined strata (eg. at Penlee Point). However, on examination of the BGS geological map (sheet no 348) (see also Fig. 4.43) it is clear that the Dartmouth Group exposed around Penlee Point is in a different structural compartment to the sequence north of Kingsand. If the southern side of the Kingsand Fault is examined it is clear that the Dartmouth Group rocks with steep attitudes at Penlee Point are in the same structural compartment as the Staddon Grit Formation 10km to the NW (Fig. 4.42). A similar length of section is present in the West Hams area between Staddon Heights and the SE end of the Warren, where the steep zone is well established. The E-W strike of bedding and faults along the West Sound coast, as opposed to the NE-SW

trends seen further east, may be attributed to dextral shear along the Kingsand compartmental fault. The apparent 4km displacement shown by this fault may be attributed to post-Variscan re-activation of a Variscan compartmental fault. As far as the examined coastal section is concerned other structural and stratigraphic relations are consistent with those observed over the South Hams part of the study area.

North Cornwall Section (Newquay)

Coastal exposures of Lower Devonian strata have been examined in Watergate Bay, between Newquay and Mawgan Porth (Fig. 4.45). This area was chosen as previous published maps (BGS sheet nos. 335 and 346) show an extensive outcrop of Dartmouth Group rocks with the coast providing continuous exposure. However, due to the orientation of structures a coast parallel section reveals little of the structure as it is oblique or near parallel to the geological strike. Mapping has been carried out using lithostratigraphic criteria utilizing the guide lines established in west Devon. This has resulted in a significant change being made to the published outcrop pattern of the Dartmouth Group rocks in the Watergate Bay area. The BGS maps (sheet nos 335 and 346) show a 3km strip of coastal outcrop for the Dartmouth Group rocks, a significant stretch of which is termed the Fish Beds. However, mapping in this study shows only a 1.25km coastal strip of Dartmouth Group rocks to be present (Fig. 4.45). It is interesting that the Fish Beds boundary of previous work coincides with the boundary between the Dartmouth Group and Meadfoot Group rocks (Bovisand Formation) of this study (applies to the contact at SX 8390 6470 only). The overall outcrop pattern in this area was previously thought to represent a westward extension of the Dartmouth Antiform from the Plymouth area (Hobson, 1976b). However, present mapping indicates the presence of a minor anticline associated to an adjacent compartmental fault which in turn forms the boundary with the Meadfoot Group to the north (Figs 4.45 and 4.46). A felsite dyke occurs at this boundary and can also be seen on the BGS sheet no. 346.

The southern margin of the Dartmouth Group rocks occurs at Fern Cavern [SX 8325 6335] and is consistent with that previously mapped. To the south of this lies further outcrops of the Meadfoot Group (Bovisand Formation). Folds in the coastal outcrops of this rock unit, exposed for a 3km stretch south of Mawgan Porth, are often recumbent and downward facing (Fig. 4.47) or upward facing to the NNW. These structures may have formed in association with thrust faults (see Fig. 4.48). The contact between the Bovisand Formation and the Staddon Formation at the north end of Mawgan Porth is a steep fault dipping 60°S. The grey

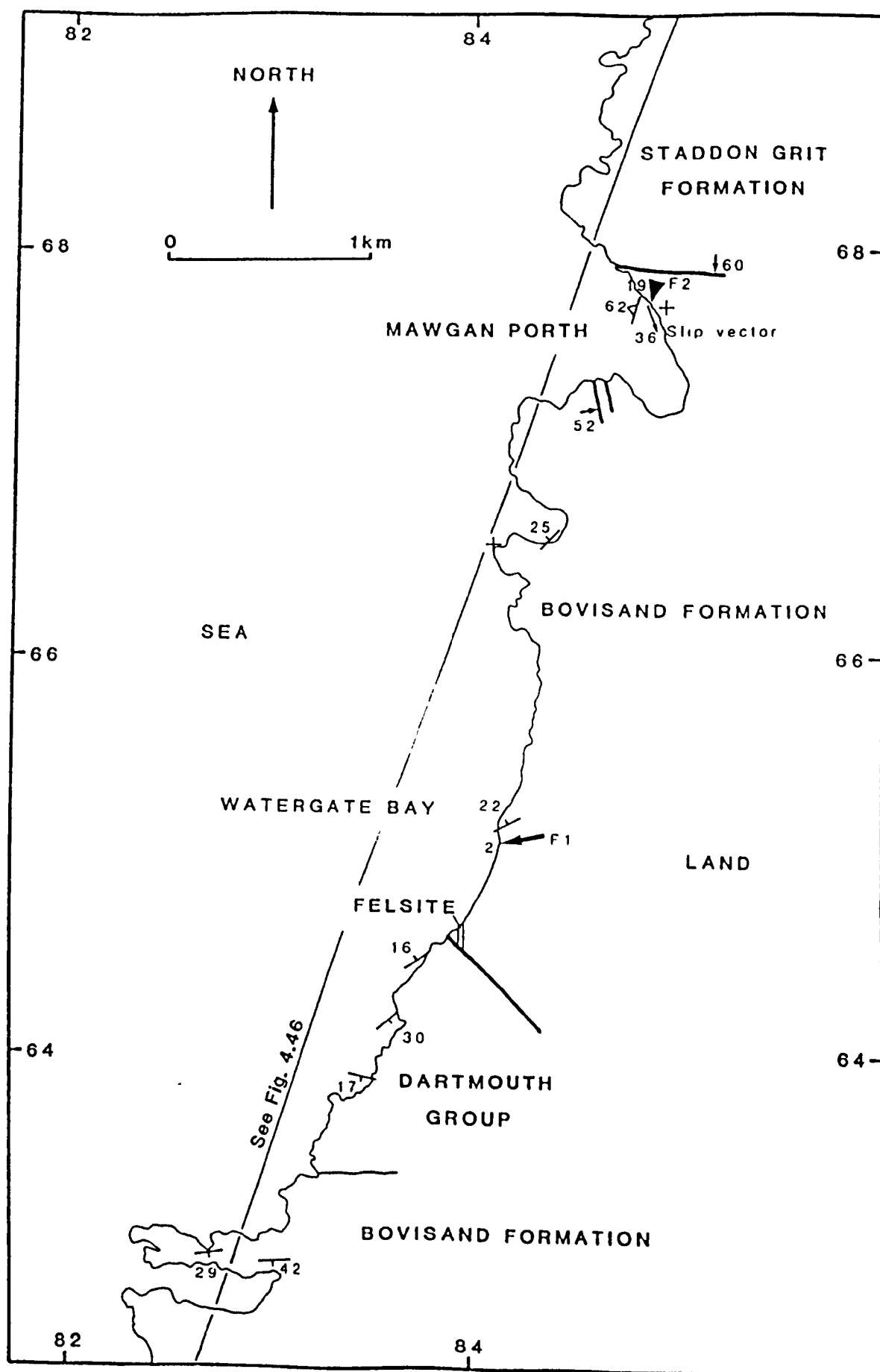


Fig. 4.45 Geological map of the Watergate Bay area in North Cornwall.

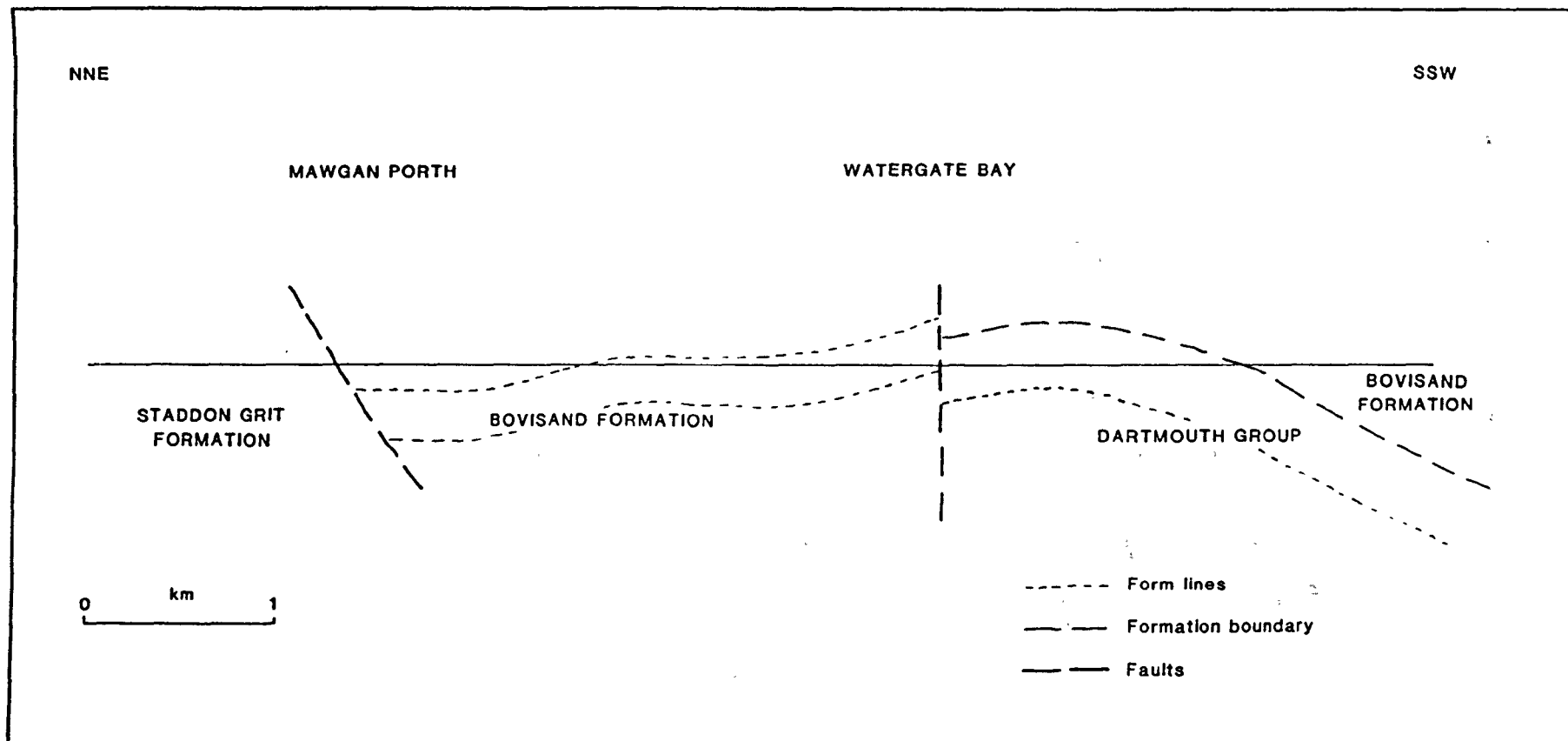
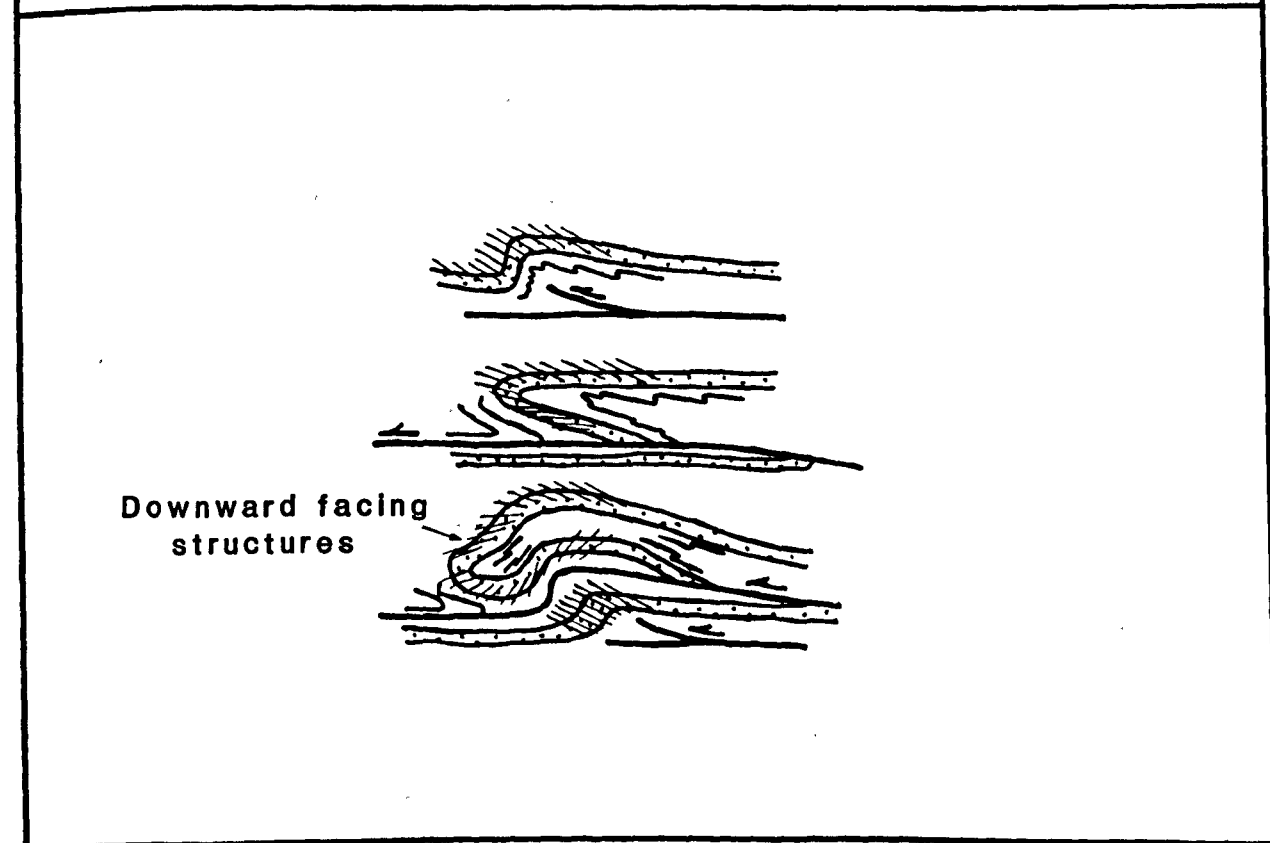
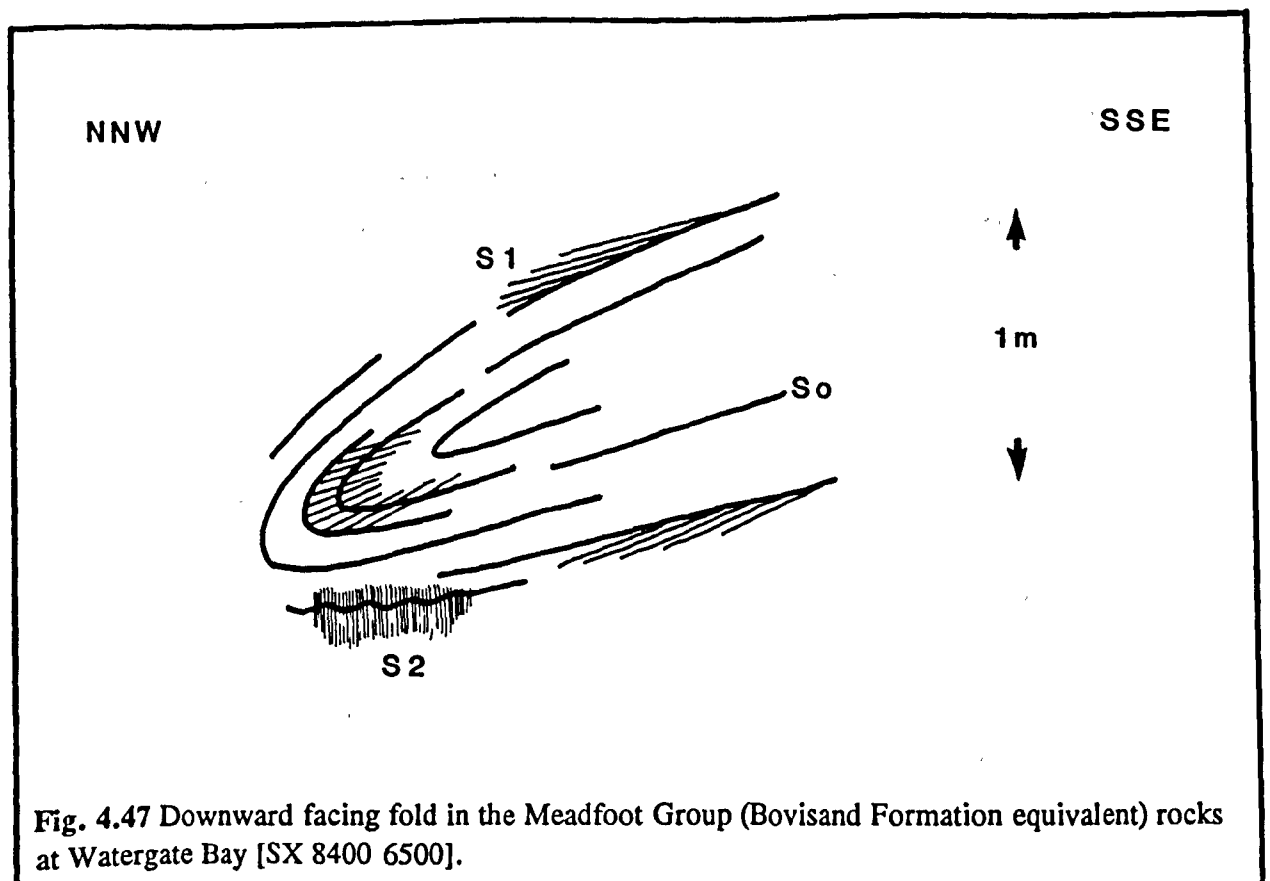


Fig. 4.46 Cross section along the north Cornish coast in the area of Watergate Bay.



pelites of the Bovisand Formation to the south of this contact are sub-horizontal (bedding and S1 cleavage). Minor thrust faults are present (050°/37°SE) and slip vectors are oriented 36°/160°. Second phase folds occur and plunge 19°/198°. This data indicates movement towards the NW perpendicular to the general trend of the coastline.

Large scale faults occur at Butt Rock to the south end of Mawgan Porth (see Fig. 4.45). These faults show apparent normal displacements but may be strike-slip (compartmental) in origin. They are oriented approximately NNW-SSE but no slip vectors were observed on the fault surfaces.

Sections either side of compartmental faults

Three cross sections have been constructed within different compartments in the area to the east and west of Plymouth. They illustrate the variation of structures in adjacent compartments and also show that deformation within each compartment proceeded independently of that in adjacent compartments. Features which illustrate the evolution of the faults can be examined in profiles through each compartment (Figs 4.49, 4.50 and 4.51) and from map patterns (see Fig. 4.42).

It is the structural components, and not the topography, that affects the outcrop pattern in each compartment. This is observed in the Jennycliff Slate Formation on the west side of the Kingsand Fault and the Staddon Grit Formation on the east side of the Kingsand Fault (Fig. 4.42). Here the faults re-orientate bedding. Certain features indicate that the faults formed during Variscan deformation. Folds and thrusts are confined to one compartment only and cannot be traced between two adjacent compartments when the compartmental fault displacements are restored. Thus they are more likely to form during folding and thrusting rather than being post-deformational in origin. This results in corresponding thrust sheets having varying widths of outcrop in adjacent compartments (compare Figs of Plymstock and Staddon Compartments). In some cases compartmental faults terminate against thrust faults (see Fig. 4.42) which suggests that they are linked at depth.

The above data indicates that some compartmental faults are not late features cutting an already deformed sequence but form during fold and thrust formation and resemble sidewall ramps. However, it is also noted that re-activation of these faults has occurred during the Permian and Tertiary periods.

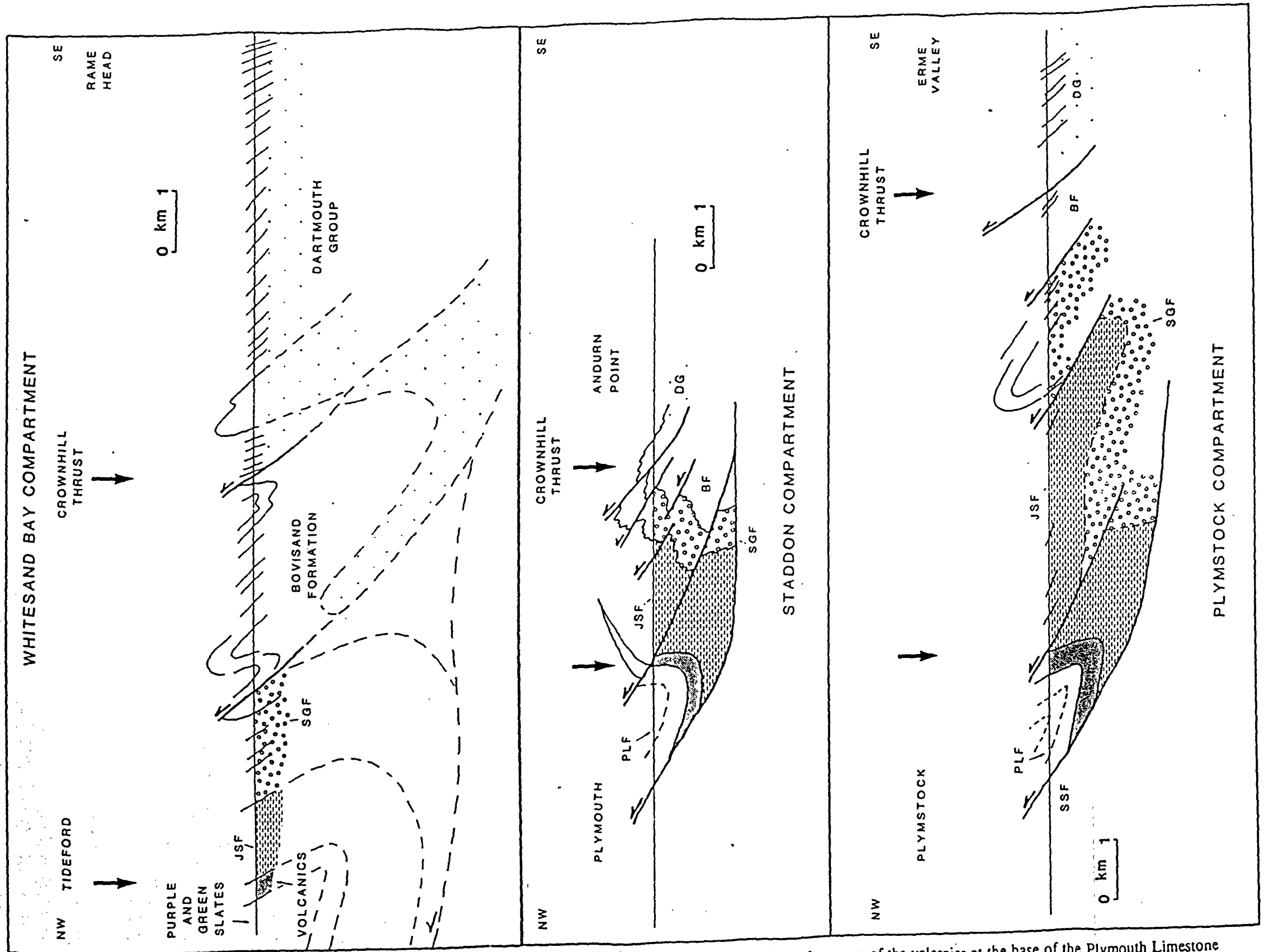


Fig. 4.49 Structural cross section through the Whitesand Bay Compartment. Arrow furthest to the NW marks the position of outcrop of the volcanics at the base of the Plymouth Limestone Formation (ie. the Plymstock Volcanic Member).

Fig. 4.50 Structural cross section through the Staddon Compartment. Initials used for the stratigraphic units as shown in Fig. 4.49.

Fig. 4.51 Structural cross section through the Plymstock Compartment. Initials used for the stratigraphic units as shown in Fig. 4.49.

4.3 STRUCTURE OF THE NORTHERN ZONE AND THE FACING CONFRONTATION

The northern zone extends northwards from Cargreen [SX 4350 6275] into central Devon between the Dartmoor and Bodmin Moor granite intrusions (Fig. 4.52). Here Upper Devonian and Lower Carboniferous strata are exposed. Structurally the area is dominated by south to south east facing and although D1 folds occur the facing is more commonly observed on the first phase cleavage. Southward facing is described from the St. Mellion, Tavistock, Mary Tavy, Tamar Valley and Lydford Gorge areas (Fig. 4.52).

4.3.1 Small scale structures

The 'outlier' of Carboniferous strata exposed in the St. Mellion area [SX 3880 6600] (Fig. 1.2), is inverted. Beds within the sequence here show grading and contain flame structures at bedding interfaces (Isaac *et al.*, 1983; Whiteley, 1984) and are also internally cross-stratified (Pl. 4.63). A southerly dipping D1 penetrative cleavage crosses the generally horizontal bedding indicating that the facing on the cleavage is to the south. These relations can also be seen at Cleave Quarry [SX 4034 6851] (see Pls 4.64 and 4.65) and Cothele Quarry [SX 4180 6801].

The rocks of the Crackington Formation (Isaac *et. al.*, 1983) exposed at Wheal Betsy, near Mary Tavy, contain a D1 cleavage which dips north west at a shallower angle than bedding. The sandstones possess bottom structures in the form of flute casts (Pl. 4.66) indicating that the beds are overturned. This bedding/cleavage association, along with the direction of younging gives south east facing on the cleavage (Pl. 4.67).

The Upper Devonian strata exposed along the shores of the River Tamar, at Hole's Hole [SX 4320 6520], contain flame structures and graded beds which indicate overturning. Northward verging D1 folds are present with horizontal long limbs and vertical short limbs and the primary axial planar cleavage dips to the south. These geometries show that the folds are downward facing towards the south (Pl. 4.68).

The Lydford Gorge area has previously been examined (Sanderson & Dearman, 1973) and southward facing structures described. This interpretation is supported on the basis of younging (overturned beds), bedding (horizontal) and cleavage (south dipping) orientations in the Upper Devonian strata (Pls 4.69 and 4.70). The same relationships also occur in the rocks exposed in the stream section at Tavistock [SX 4825 7455].

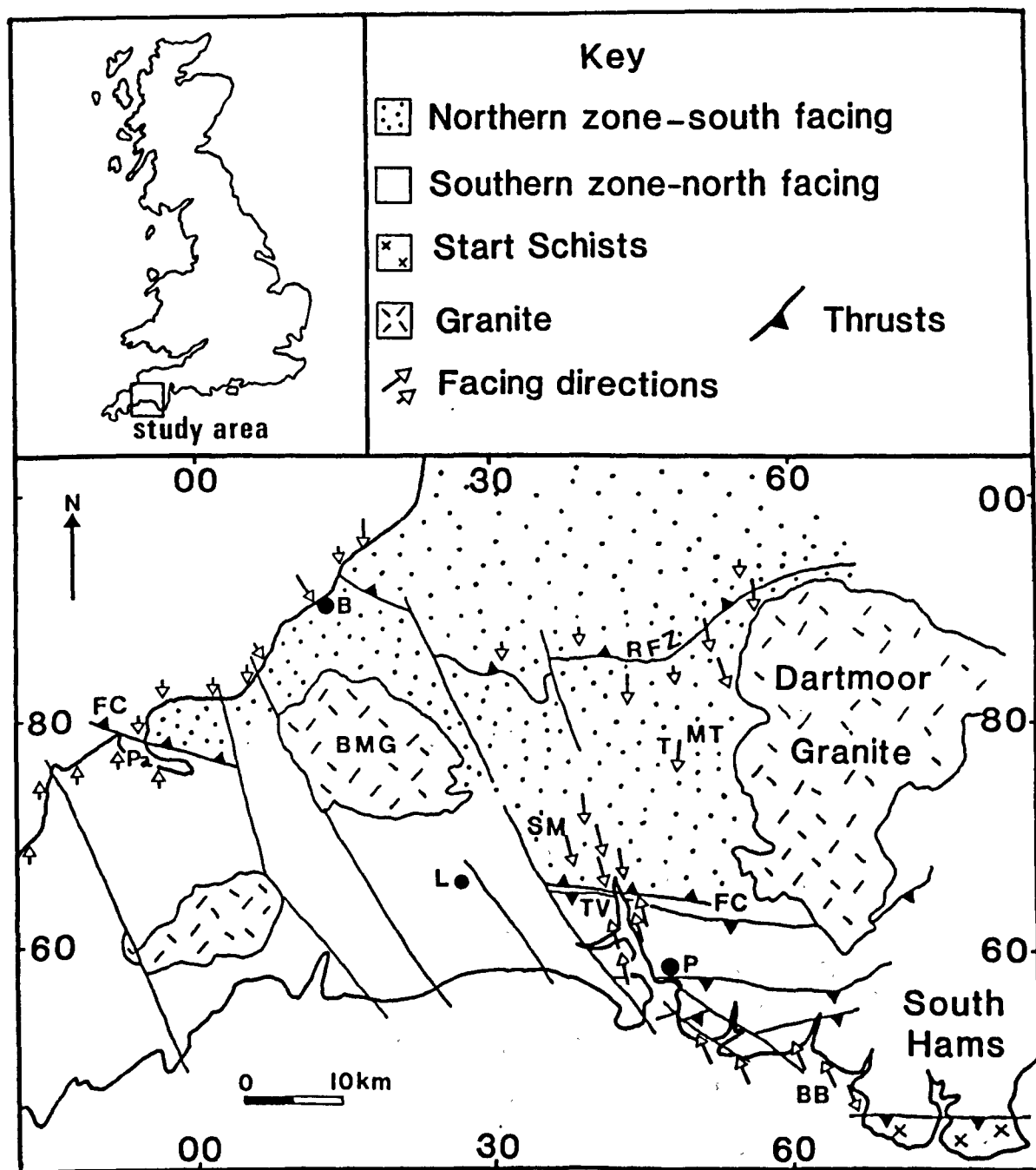


Fig. 4.52 Map of the northern and southern zones showing the distribution of fold facing directions in central SW England. Arrows with long tails are observations made during this study. Short-tailed arrows are observations made by others (referred to in the text). B, Boscastle; BB, Bigbury Bay; BMG, Bodmin Moor Granite; FC, Facing Confrontation; L, Liskeard; MT, Mary Tavy; P, Plymouth; Pa, Padstow; RFZ, Rusey Fault Zone; T, Tavistock; TV, Tamar Valley.



Plate 4.63 Inverted cross bedding in Carboniferous sandstones at St. Mellion [SX 3890 6550].



Plate 4.64 Inverted graded bedding with first phase cleavage in a muddy horizon indicating south facing; Cleave Quarry [SX 4034 6851]. Looking west. Height of photograph is 8cm.



Plate 4.65 Cleavage/bedding relationships in Carboniferous rocks on the east shore of the River Tamar [SX 4160 6500]. The beds are inverted and south east facing on the cleavage is indicated. Looking north east.

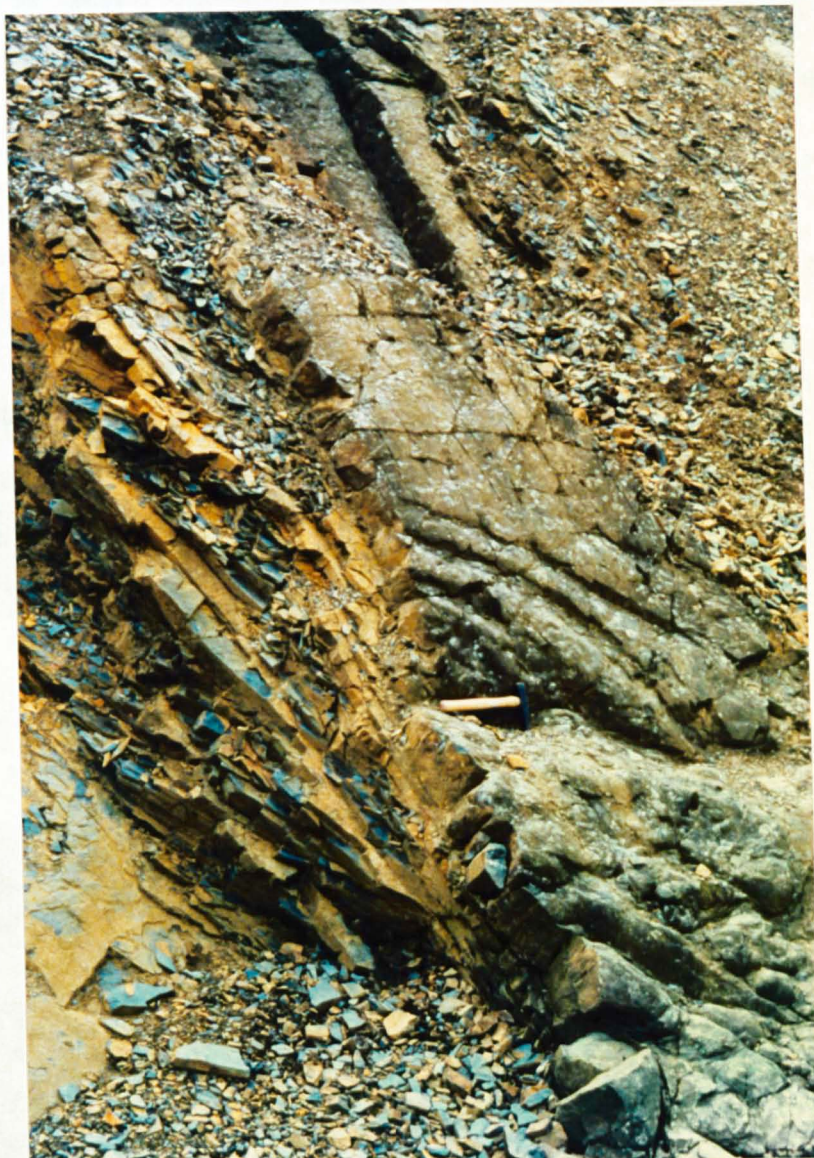


Plate 4.66 Flute casts on the inverted bases of sandstone units in the Carboniferous rocks at the Wheal Betsy section [SX 5090 8070] near Mary Tavy.



Plate 4.67 Cleavage/bedding relationships in the Wheal Betsy stream section [SX 5090 8070] near Mary Tavy. Beds are inverted, and with cleavage at a lower angle to bedding, south east facing on the cleavage is indicated. Looking north east.



Plate 4.68 North verging fold at Hole's Hole [SX 4320 6520]. The sheet dip is horizontal and the beds are inverted with a south dipping cleavage. This gives south facing. Looking east.



Plate 4.69 Cleavage/bedding geometries at Lydford Gorge [SX 5020 5100]. Looking east. (see Pl. 4.70 for detail).



Plate 4.70 Close up of Pl. 4.69 showing graded units with sharp bases and fine tops cut by the first phase cleavage indicating facing to the south. Looking south. Height of photograph ca. 10cm.

The above data indicates that the Carboniferous outlier described at the above localities (see Fig. 1.2) represents the lower overturned limb of a southwards closing fold nappe, indicating transport towards the south (Fig. 4.53). This conclusion is based on the observations made during this study and is consistent with previously published data (Gauss, 1967, 1973; Dearman, 1970, 1971; Roberts & Sanderson, 1971; Freshney *et al.*, 1972; Sanderson & Dearman, 1973; Hobson & Sanderson, 1975, 1983; Sanderson, 1979; Shackleton, 1982). However, other work (Isaac *et al.*, 1982; Selwood & Thomas, 1984, 1985, 1986a; Selwood *et al.*, 1985) has failed to realise the regional importance of the relationships described at the above localities. The existence of large tracts of land with southerly facing fold directions is at variance to the consistent northerly facing directions of the southern zone. The area where these two zones of distinct structural style meet is therefore investigated.

4.3.2 The facing confrontation and its development

A facing confrontation of first phase folds was initially described on the north Cornish coast near Padstow [SW 9200 7500] (Gauss, 1967, 1973; Dearman, 1970, 1971; Roberts & Sanderson, 1971; Sanderson & Dearman, 1973; Hobson & Sanderson, 1975, 1983; Sanderson, 1979; Shackleton *et al.*, 1982) where a belt of north facing, first phase structures are developed in the south and a zone of south facing, first phase structures to the north. With the confrontation defined at the coast, subsequent investigations took place in central Devon where south or south east facing was discovered in the Mary Tavy, Lydford and Okehampton areas (Sanderson & Dearman, 1973). These structures oppose the northward directed early folds of SW Devon and Cornwall and so the above authors inferred a confrontation similar to that seen further to the west. However, it was not pinpointed precisely in the area north of Plymouth.

The existence of south facing folds at the southern margin of the Culm Measures is well documented (Sanderson & Dearman, 1973; Hobson & Sanderson, 1983). Fold axial planes are vertical at Bude, but further to the south they invariably dip to the north (Crackington Haven) and in some cases are horizontal (Millook Haven) (Sanderson, 1979). At these localities, and as far south as the Rusey Fault Zone, it can be demonstrated that facing is undoubtedly in a southwards direction. However, it is the area to the south of the Rusey Fault Zone that has caused a difference of opinion in recent years. Several workers have described the area between Rusey and Polzeath as facing south with respect to D1 folds

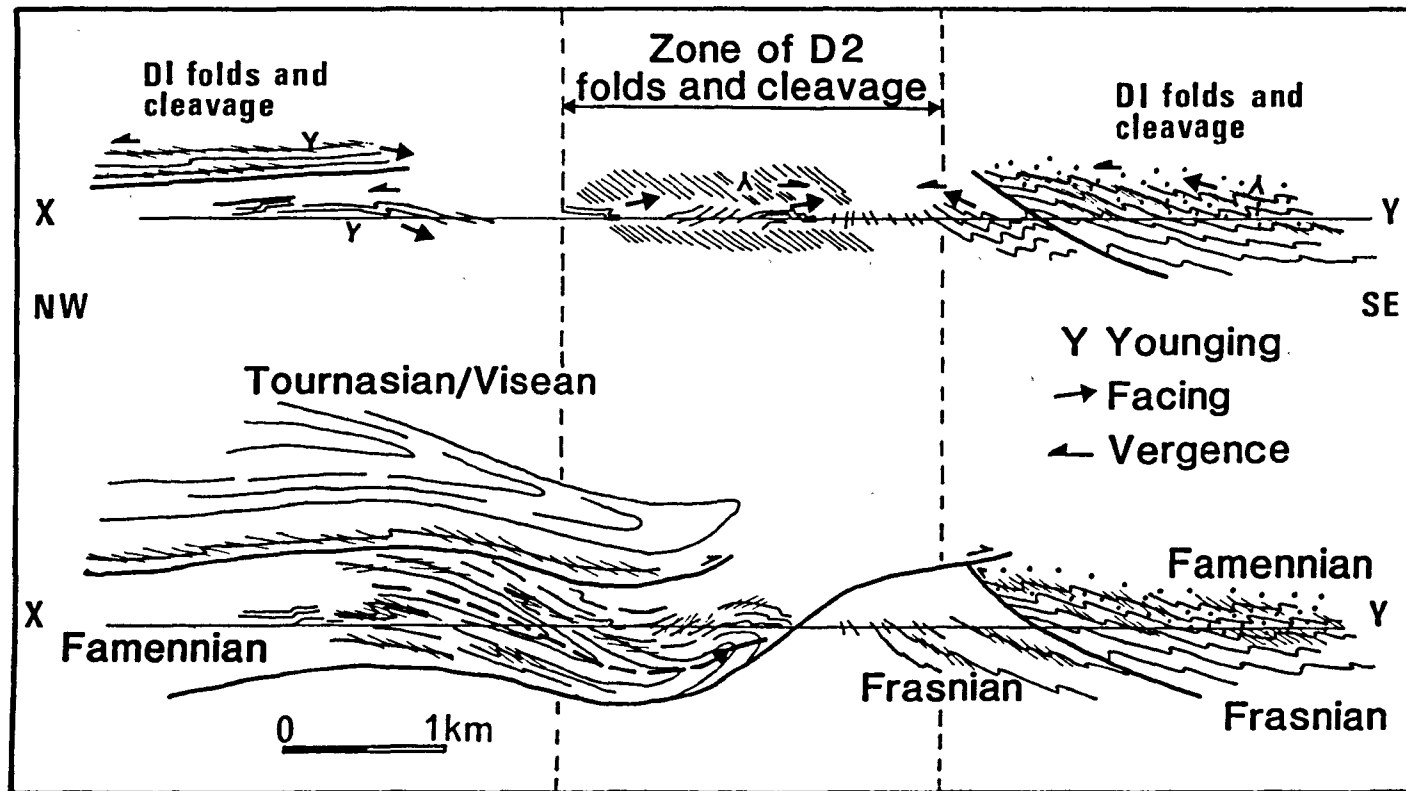


Fig. 4.53 Structural relationships along a NW-SE transect through the facing confrontation (top). Line X-Y in Fig. 4.54. Interpretation of the facing confrontation (bottom).

(Roberts & Sanderson, 1971; Gauss, 1973; Sanderson & Dearman, 1973; Hobson & Sanderson, 1975; Shackleton *et al.*, 1982). However, subsequent work has been carried out by a group from Exeter University in this area and in the equivalent area along strike to the north of Plymouth, the area which is equivalent to the northern zone described here. In contrast to the earlier work they have described the whole zone in terms of northwards transport with respect to the first phase structures (Isaac *et al.*, 1982; Selwood & Thomas, 1985, 1986a) but in many cases they do not describe the facing on the first phase structures but on northerly transported D2 structures. These findings are contrary to the results of the present study.

During the present research programme the confrontation of north and south facing first phase folds has been accurately located as passing through Cargreen [4350 6275], 8km north of Plymouth in the Tamar Valley (Fig. 4.54). Folds immediately to the south of Cargreen are northward and upward facing with respect to the D1 slaty cleavage and their vergence is to the north. Thrusts which disrupt this essentially upright Famennian sequence also have a movement direction to the north or north west. To the north of Cargreen the strata are predominantly overturned and facing on the cleavage is to the south or south east. Thus, at Cargreen there is an E-W trending, facing confrontation which is interpreted here as a northerly dipping thrust (Fig. 4.53). Similarly, Gauss (1973) interpreted the facing confrontation at Padstow as a northerly dipping thrust. There is a remarkable contrast between the two structural zones described. The products of the northward transporting Variscan deformation in the southern zone are upright to northerly overturned, north verging and north facing folds (see Section 4.2). Although large scale thrust sheets are produced during this deformation episode there is no regional scale overturning of strata. This is in contrast to the northern zone, to the north of the facing confrontation, where thrust-related fold nappes give rise to large scale overturning of strata.

Work by the Exeter Group has covered this area to the north of Plymouth. They postulate that the fold nappes were transported towards the north by gravity sliding (Isaac *et al.*, 1982; Selwood & Thomas, 1985, 1986a) and suggest that southward movement is not encountered until the Rusey Fault is crossed (see Fig. 4.54). This study indicates, however, that the early folds between the Rusey Fault Zone and Cargreen indicate nappe transport towards the south. The early folds in this zone are then overprinted by northerly-directed structures which are described as being D2 in age.

The cleavages which form as products of the D1 deformation have different forms north and south of the confrontation. The slaty cleavage in the northern zone is flat-lying and

the facing is towards the south, whilst the D1 cleavage in the southern zone dips at 30° to 40°S or SE and the facing is towards the north or NW (see Figs 4.53 and 4.54). These cleavages probably formed at different times as a result of progressive deformation from south to north and represent the earliest deformation in their respective areas. At the confrontation there is a zone of intense deformation. The flat-lying D1 (North) cleavage is deformed into northward verging folds (D2) which possess an axial planar crenulation cleavage, dipping at 40° to 50°S. Roberts & Sanderson (1971) describe a similar association of cleavages on the north Cornish coast. Burton & Tanner (1986) also describe a D2 zone in the Liskeard area which if projected eastwards along strike would lie well into the southern zone described here.

4.3.3 The area east of Dartmoor

Structural relations on the east side of the Dartmoor Granite bear close resemblance to those described above for the Tamar Valley. The following descriptions and views are based on the data contained in a BGS memoir (Selwood *et al.*, 1984; see also Ussher, 1913). This guide, as well as describing the relevant stratigraphic units, also presents structural maps and interpretive evolutionary cross sections for the area, the important features of which are presented in Figs 4.55 and 4.56.

The details reviewed here are contained in Chapter 2 of the above memoir (p. 6-17) and is also in part based on the work of Waters (1970). Detailed maps are not presented in this memoir but the general map patterns show the distribution of the Devonian and Carboniferous structural units. Many of the units are separated by thrust faults and are thus contained in thrust sheets. The thrusts are shown to have consistent movement directions towards the NW. However, it is the internal structure of these thrust sheets which is of vital consequence. West of the Bovey Basin the Denbury and Ugbrooke Units, indicate northwards transport of the strata. This has also been observed in the footwall to the Holne Thrust (in the Liverton thrust sheet) where north facing folds occur. However, throughout the remainder of the Liverton and Islington Units facing, and hence the direction of transport, has not been determined in the recumbent and isoclinal folds of Upper Devonian and Carboniferous strata. Folds in the Teign Valley Unit to the north are upright and at its southern limit overturned towards the south (Fig. 4.56). A facing confrontation therefore occurs to the east of the Dartmoor Granite and has a similar geometry to that further west (see Figs 4.53, 4.55 and 4.56).

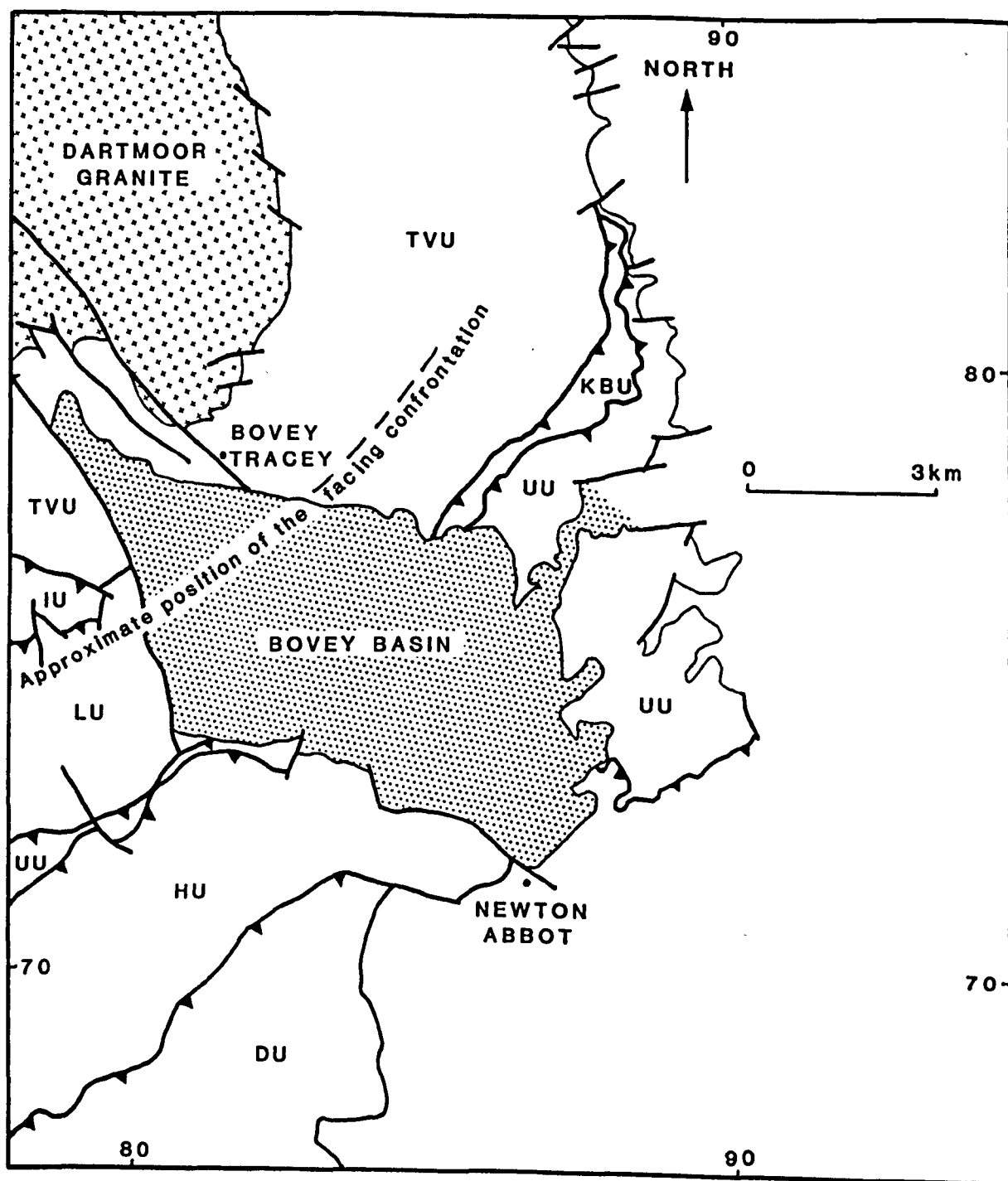


Fig. 4.55 Structural and stratigraphical relations on the east side of the Dartmoor Granite (DU - Denbury Unit; HU - Holme Unit; IU - Islington Unit; KBU - Kate Brook Unit; LU - Liverton Unit; TVU - Teign Valley Unit; UU - Ugbrooke Unit) (after Selwood *et al.*, 1984).

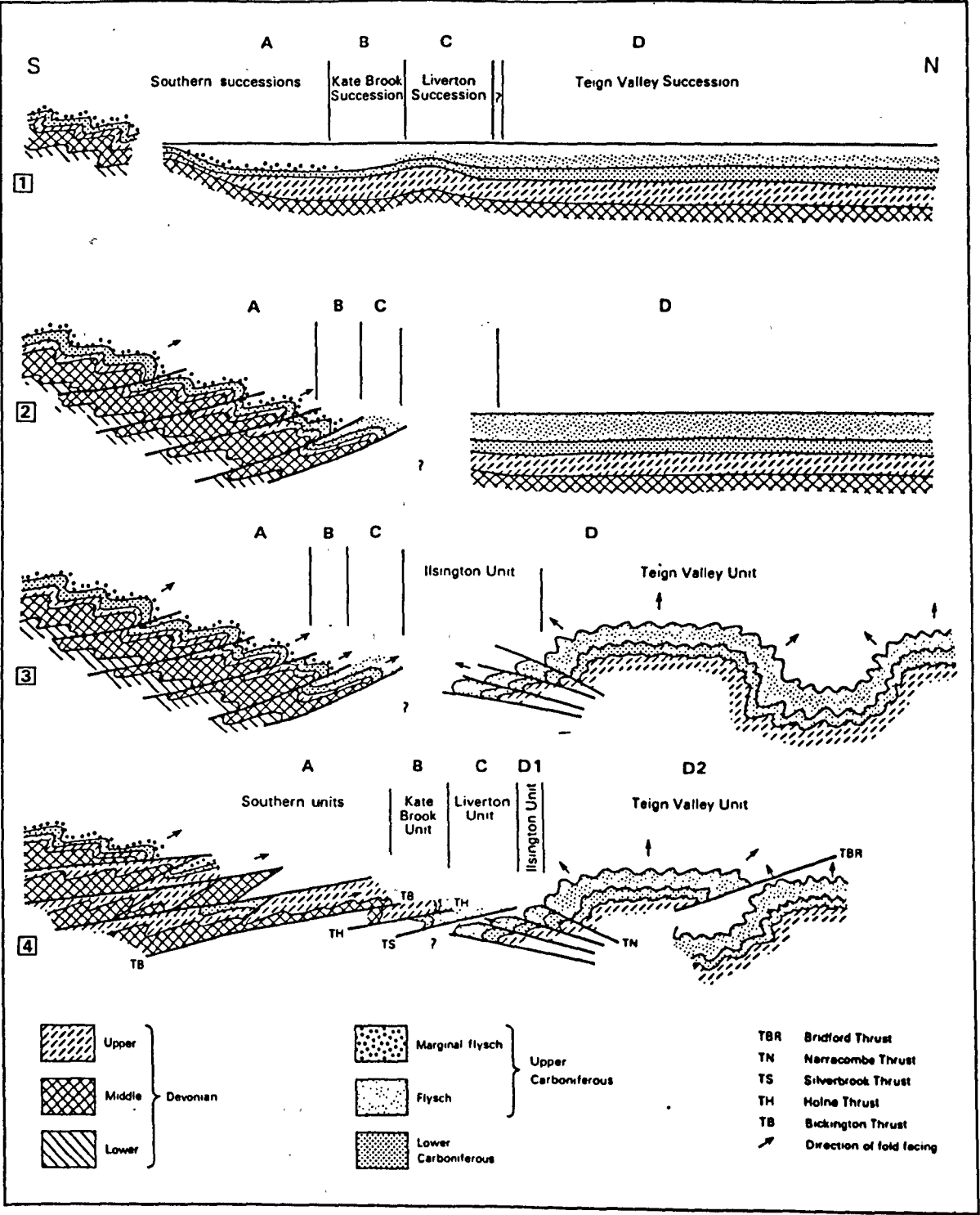


Fig. 4.56 Structural evolution of the Devonian and Carboniferous rocks of the Newton Abbot District (after Selwood *et al.*, 1984).

East of the Bovey Basin the northwards facing folds of the Kate Brook Unit are separated from upright folds of the Teign Valley Unit by the northerly directed Holne Thrust. This implies that the area of south facing present further west has been concealed by structurally higher level thrust sheets.

4.3.4 A foreland basin model

Any tectonic model for the evolution of SW England has to account for the following features.

1. A southern zone of northerly facing structures. This includes northwestward verging folds, thrusts with a northwesterly sense of movement, and a penetrative cleavage which dips to the south east. This zone is composed of Devonian rocks.
2. A northern zone of flat-lying, recumbent fold nappes which face south or south east, with an associated flat-lying penetrative cleavage. This zone is composed of rocks of Late Devonian and Early Carboniferous age.
3. A triangle zone and facing confrontation where the southern and northern zones meet.
4. A northern zone where inverted strata, on the lower limbs of the recumbent fold nappes, generally lie above older rocks.
5. A second phase of deformation producing north verging D2 folds intensely developed in the vicinity of the facing confrontation.

It is now accepted that deformation and sedimentation migrated northwards across SW England during Late Devonian/Early Carboniferous times (Dearman, 1971; Dodson & Rex, 1971; Shackleton *et al.*, 1982; Isaac *et al.*, 1983; Sanderson, 1984; Selwood & Thomas, 1986b). The Tournasian and Visean strata forming the fold nappes in the St. Mellion area are immature, poorly sorted deposits containing plant debris indicating shallow water, deltaic sedimentation having a source to the south (Whiteley, 1981, 1982, 1984). Isaac *et al.* (1983) and Turner (1986) have interpreted these rocks as flysch deposits and Selwood & Thomas (1986b) have suggested that they accumulated within a fore-deep in advance of a northerly migrating deformation front. Whilst this view is fully endorsed it is not agreed that fold

nappes then glided northwards under the influence of gravity (Isaac *et al.*, 1982; Selwood & Thomas, 1985, 1986a; Turner, 1986). Instead, the small scale structures demonstrate that the larger structures close to the south and face south or south east. Northwards facing, first phase structures are not observed in the northern zone.

The foreland basin deposits (Allen & Homewood, 1987; Beaumont, 1981) were deformed soon after deposition (Selwood & Thomas, 1988) producing large, southerly facing fold nappes (see Fig. 4.57). It is the overturned limbs of these nappes which are now mainly exposed in the northern zone. Clearly underthrusting of the foreland basin flysch deposits has occurred. Such a situation is documented in the Rocky Mountain foothills where a triangle zone has developed (Price, 1981; Butler, 1982; Jones, 1982). In essence the migrating thrust front 'chisels' its way under the foredeep flysch deposit, which, although remaining *in situ*, are thrust backwards towards the hinterland (cf. Banks & Warburton, 1986).

In SW England during such an underthrusting process the foredeep beds became overturned. This could only be achieved by employing the idea of a rolling hinge to the nappes (Shackleton, 1979; Platt *et al.*, 1983, their Fig. 16a) in which successive material points move through the hinge on to the lower, overturned limb of the nappe (points A, B, C and D in Fig. 4.58). On the upper diagram of this figure point 'A' is above point 'X'. As material points move through the hinge point 'A' will eventually lie above point 'Y'. The lower limb is thus dragged downwards. This procedure allows the overturning of the nappe pile to occur at a slower rate than the underthrusting process and overturning of younger strata over older is achieved. Conventional backthrust movement would emplace older strata on top of younger whilst the nappe pile moved southwards. The tips of the lower limb of the fold nappe and underthrusting proceed in a 'caterpillar track' fashion, in what is described as underpeeling. Each nappe progressively accretes itself onto the front of the advancing thrust sheets (see Fig. 4.59). No material moves south towards the hinterland. It all moves northwards but the unconsolidated flysch deposits are thrust in a relative southward direction over the underthrusting, northward moving thrust belt. Such a model also explains the intense development of second phase folds in the region of the confrontation. First phase structures were independently developed in the north and south, and when the underthrusting occurred those of the south overprinted the flat lying south facing cleavage of the north in the region of the confrontation, and produced a strong D2 crenulation fabric. The D2 structures have a northerly sense of movement due to the continuing northwards migration of the deformation front.

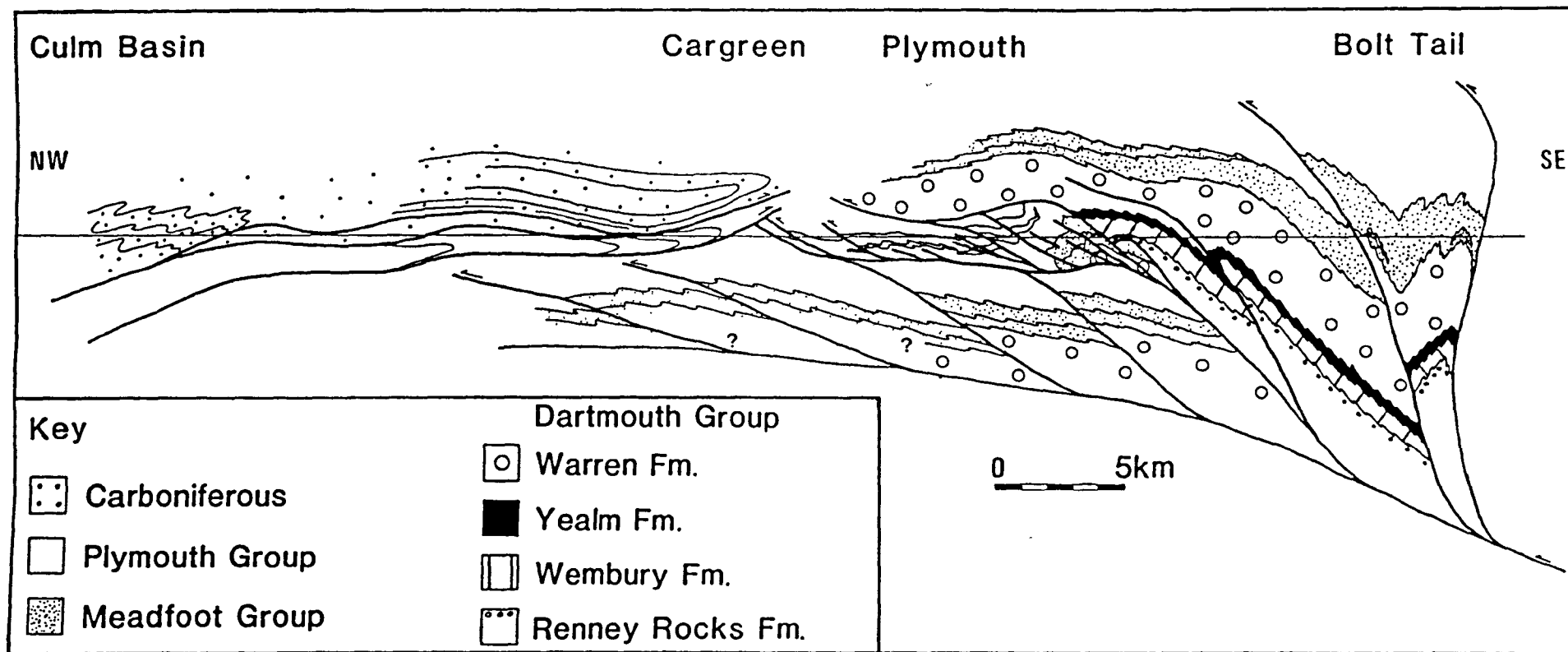


Fig. 4.57 Structural cross section showing the possible deep structure and the form of the facing confrontation in relation to the southern zone.

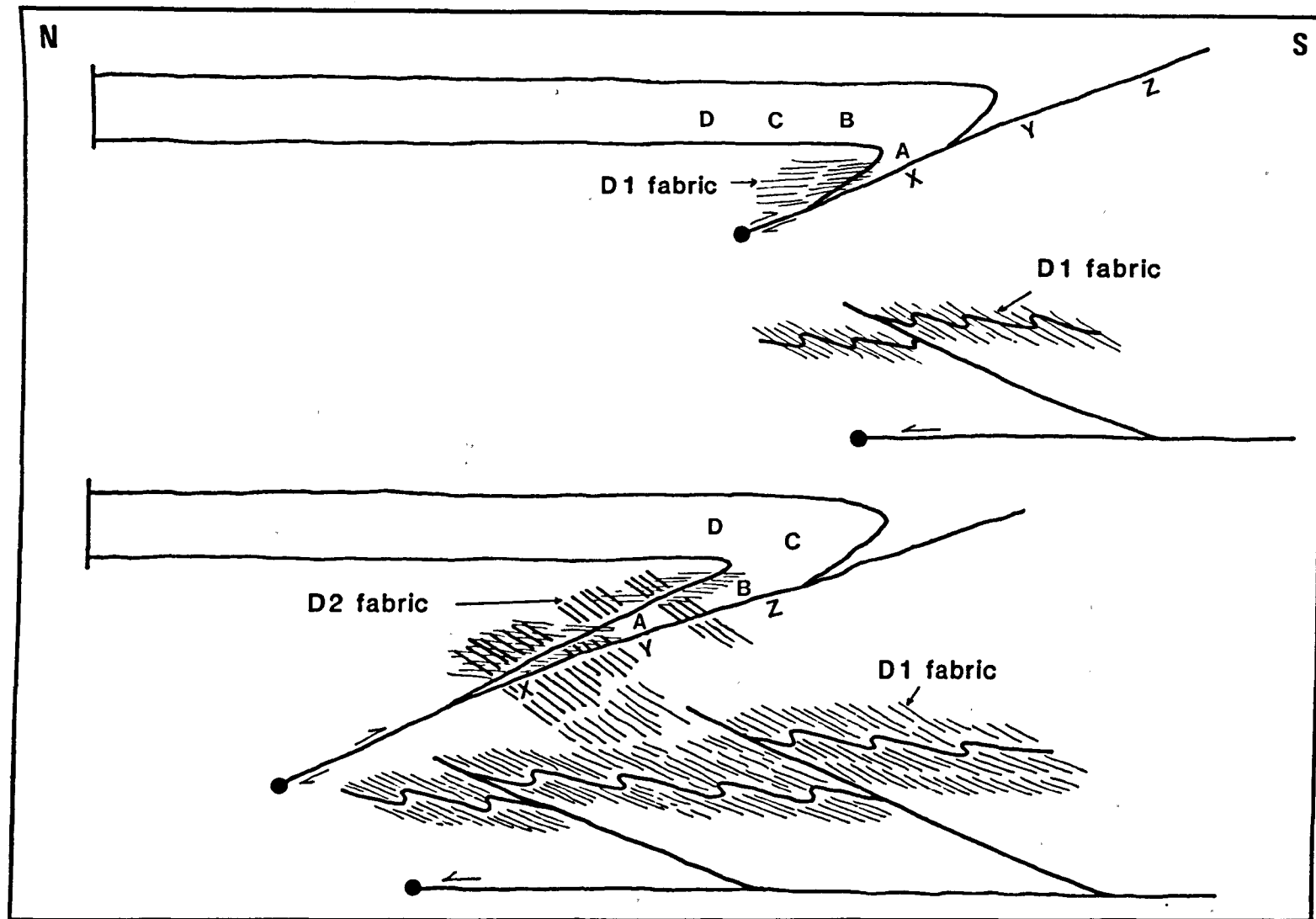


Fig.4.58 This figure illustrates how movement along the major backthrust occurs at a faster rate relative to the overturning of the overlying nappe pile (further explanation in the text). The diagram also shows how the cleavage of the south overprints the cleavage of the north, resulting in the formation of a southward dipping crenulation cleavage. A, B, C, D and X,Y,Z are reference points which demonstrate relative translations.

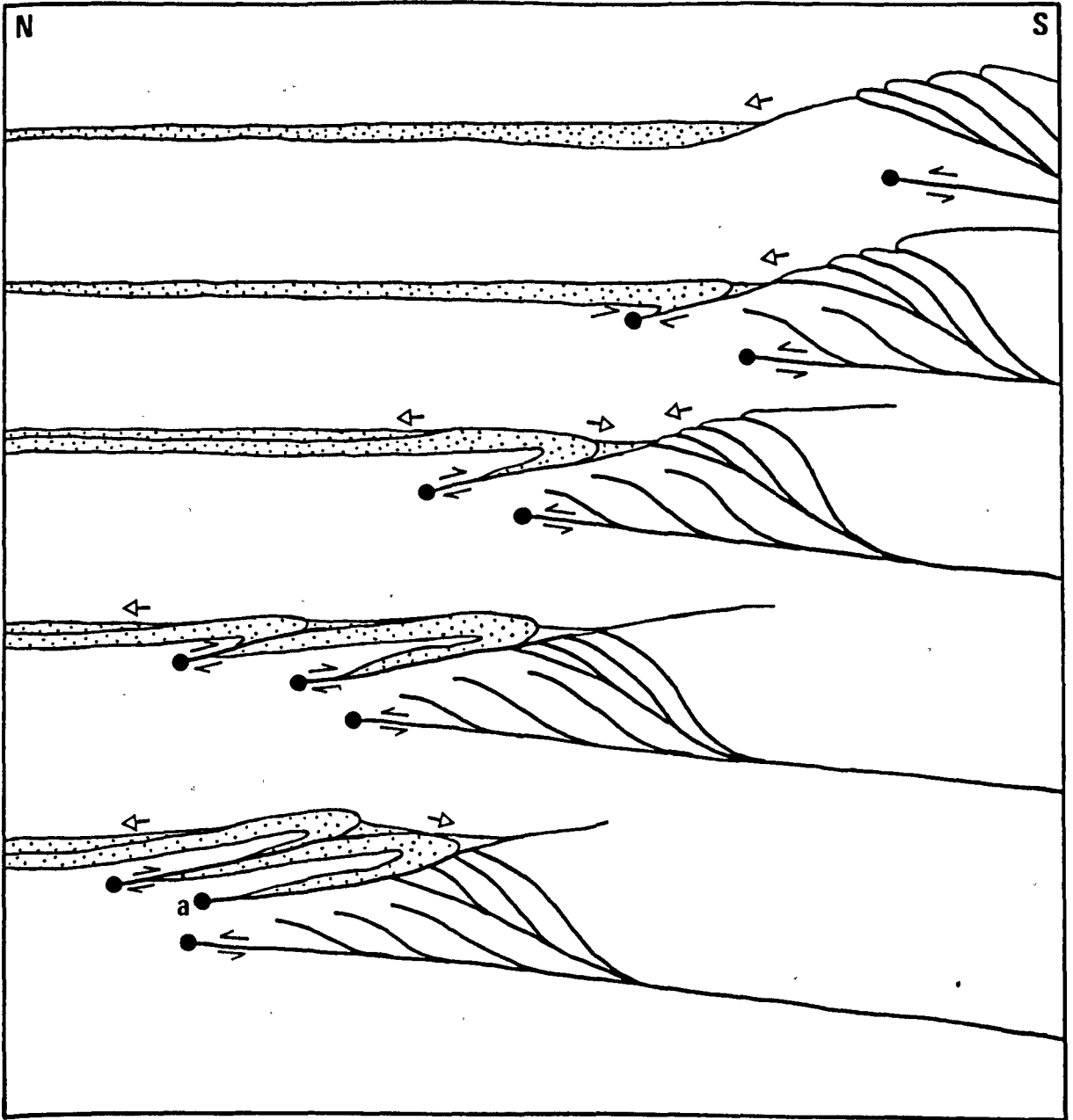


Fig. 4.59 Schematic evolutionary model showing the style of deformation at the southern margin of the Carboniferous basin in SW Devon, an inverted basin margin. In the lowest sketch the middle thrust (a) becomes inactive. Open arrows indicate sediment influx and half arrows indicate movement on an active thrust.

4.3.5 Deep structure

There are a number of possible model cross sections which can represent the deep structure of SW England (Fig. 4.60). They involve either a shallow or deep 'pop-up' structure (cf. Shackleton *et al.*, 1982) or a localised facing confrontation scenario. The back steepening at the southern end of the sections may be due to a deep crustal backthrust (Coward & Smallwood, 1984). However, back steepening may also have been caused by normal foreland-propagation of thrusts and folds. A number of issues arise out of these proposed models: does the backsteepening form from backthrusting or thrust stacking?; is the Carboniferous flysch within a shallow pop-up, deep pop-up or involved in conventional thrusting with the underlying Devonian sequence? This latter model would only have to involve local backthrusting at the facing confrontation. The presence of flysch deposits in the Clum Trough, which experienced syn-sedimentary thrusting whilst still in an unconsolidated state during the Westphalian (Whalley & Lloyd, 1986; Enfield *et al.*, 1985), can be incorporated in each of the above models. All of these models are compatible with offshore deep seismic profiles (BIRPS & ECORS, 1986).

4.4 KEY POINTS

1. Two structural zones occur in SW Devon; a southern zone and a northern zone. They have contrasting structural styles.
2. The southern zone is characterized by northwards facing on steep to gentle south dipping structures. In the far south of the zone minor structures indicate southward directed movements. This is attributed to back steepening by foreland propagating thrust stacks or backthrusting. Regional overturning in the form of large scale nappes is not a feature of the southern zone.
3. The northern zone is characterized by flat lying structures, which face to the south or south east, and by overturned nappes.
4. The two structural zones meet at a confrontation which is interpreted as a triangle zone involving both north and south dipping thrusts. The south facing structures overlie a fault with backthrust sense in relation to the south dipping Variscan structures.
5. The northward propagating structures underthrust Upper Devonian and Lower Carboniferous flysch (foreland deep) deposits. The rocks above the decollement,

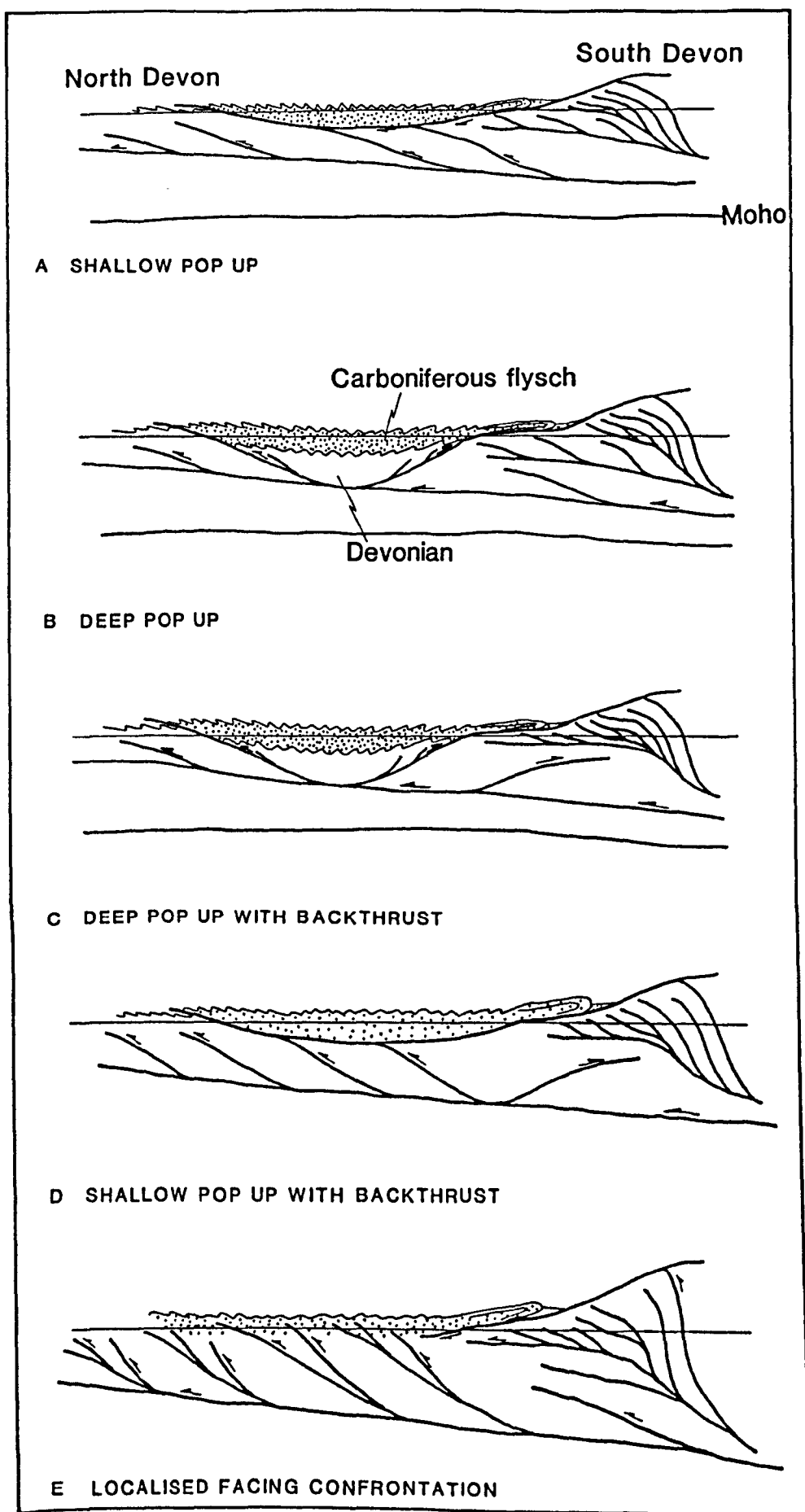


Fig. 4.60 Sections representing the possible deep structure of central SW England.

produced as a result of underthrusting, were deformed into south facing fold nappes of which the overturned limbs are now exposed.

6. Overprinting of the northern structures by those of the south gives rise to D2 structures which are most intense in the vicinity of the confrontation. D2 structures indicate northerly directed transport.

CHAPTER 5

A REVIEW OF THE STRUCTURAL DEVELOPMENT OF THE START SCHIST COMPLEX

5.1 INTRODUCTION

The Start Schist Complex (SSC) occurs at the southern tip of the South Hams peninsula (see Fig. 4.52). It is bounded to the east, south and west by the coast. To the north its boundary with the rocks of the Lower Devonian Meadfoot Group is marked by a distinct break of slope between low ground composed of slates to the north and higher, more resistant ground composed of schists to the south. The boundary runs E-W and is almost straight in outcrop pattern. It is interpreted as a sub-vertical tectonic break and is referred to here as the Start Fault.

The rocks of the SSC are studied in order to evaluate the nature of the northwards progressive deformation which swept from south to north during the Variscan Orogeny (Matthews, 1977). Hobson (1977) states that the SSC structures parallel those in the proven Devonian rocks to the north indicating that the timing of the SSC deformation was indeed Variscan. An investigation into the attitude of structures relative to those north of the boundary shows that the history of deformation is progressive across the Start Fault and that the deformation events within the SSC are wholly Variscan. The SSC has generated a great deal of interest over the years and this may be attributed to their relatively high degree of deformation and metamorphism relative to the slates to the north. This has led some workers to suggest that the Complex was in fact Archean in age (Bonney, 1884). The fact that the oldest structures present within the SSC appear to be Variscan led Marshall (1965) to believe that the rocks are Silurian to Devonian in age and not Archean.

The early work of Bonney (1884) and Ussher (1904) involved mapping and general descriptions of the SSC and this was followed by a comprehensive petrological study and re-mapping programme by Tilley (1923). Phillips (1961) investigated the minor structures of the Complex and related them to those in the slates further north. This prompted Marshall (1965) to make a more detailed study along the same lines. Hobson (1977) supplemented this with his own field data and related the SSC to the Variscan orogen on a regional scale. The present study collates the previous work in order to understand the deformation history across the Start Fault. This is aided by the detailed analysis of the small scale structures in the slates in relation to their regional significance. It has not been possible to map the SSC although the

structures adjacent to the boundary have been noted. Revisions to the published views are put forward but in general the work of Marshall (1965) is supported.

Essentially two rock units exist within the SSC (Ussher, 1904; Tilley, 1923; Marshall, 1965; Hobson, 1977) and these are referred to as the Green Schists and the Quartz Mica Schists (QMS) (Marshall, 1965). Their distribution is governed by a major D2 antiform (Ussher, 1904; Tilley, 1923; Marshall, 1965; Hobson, 1977) which plunges to the WSW (see Fig. 5.1). This major fold is picked out by a layer of Green Schists within the QMS (see BGS sheet no. 356). It has been argued that the QMS are just one unit and that they have been repeated by faulting. Another hypothesis is that the Green Schists occupy the core of a recumbent D1 fold (Hobson, 1977). However, Tilley (1923) and Marshall (1965) conclude that there is an upper unit of QMS (Bolt Mica Schists) and a lower unit (Start Mica Schists) which results in a succession comprising three units.

It seems likely that the Green Schists are altered lavas and tuffs (Tilley, 1923; Marshall, 1965) whilst the QMS are metamorphosed sediments which were mainly claystones with sandstones and some volcanics. Marshall (1965) has shown that the upper (younger) Bolt Mica Schists are coarser deposits than the lower (older) Start Mica Schists. The Green Schists are predominantly metasediments (grey schists) with subsidiary volcanics. Due to this interbedded nature they were referred to as the Composite Schists (Tilley, 1923; Marshall, 1965).

Fossils are not found in the SSC and therefore dating the rocks is a problem. The only ages published for the SSC are those resulting from radiometric dating. These indicate that metamorphism (possibly retrograde) took place ca. 290 to 310 million years ago (Dodson and Rex, 1971). The grade of metamorphism experienced by the SSC is upper chlorite grade in contrast to the lower chlorite grade reached by the slates to the north of the Start Fault (Marshall, 1965). Detailed sedimentological investigations have not been undertaken and this is probably due to the degree of metamorphism and structural deformation affecting the rocks. However, occasional cross bedding has been observed in some of the thicker psammitic units indicating the local way up (Marshall, 1965).

5.2 DEFORMATION HISTORY OF THE START SCHIST COMPLEX

Phillips (1961) and Marshall (1962, 1965) recognise several phases of folding in the SSC and they both describe and interpret the minor structures of the area. Marshall (1965) describes four phases of deformation. The D1 folds are described as being initially

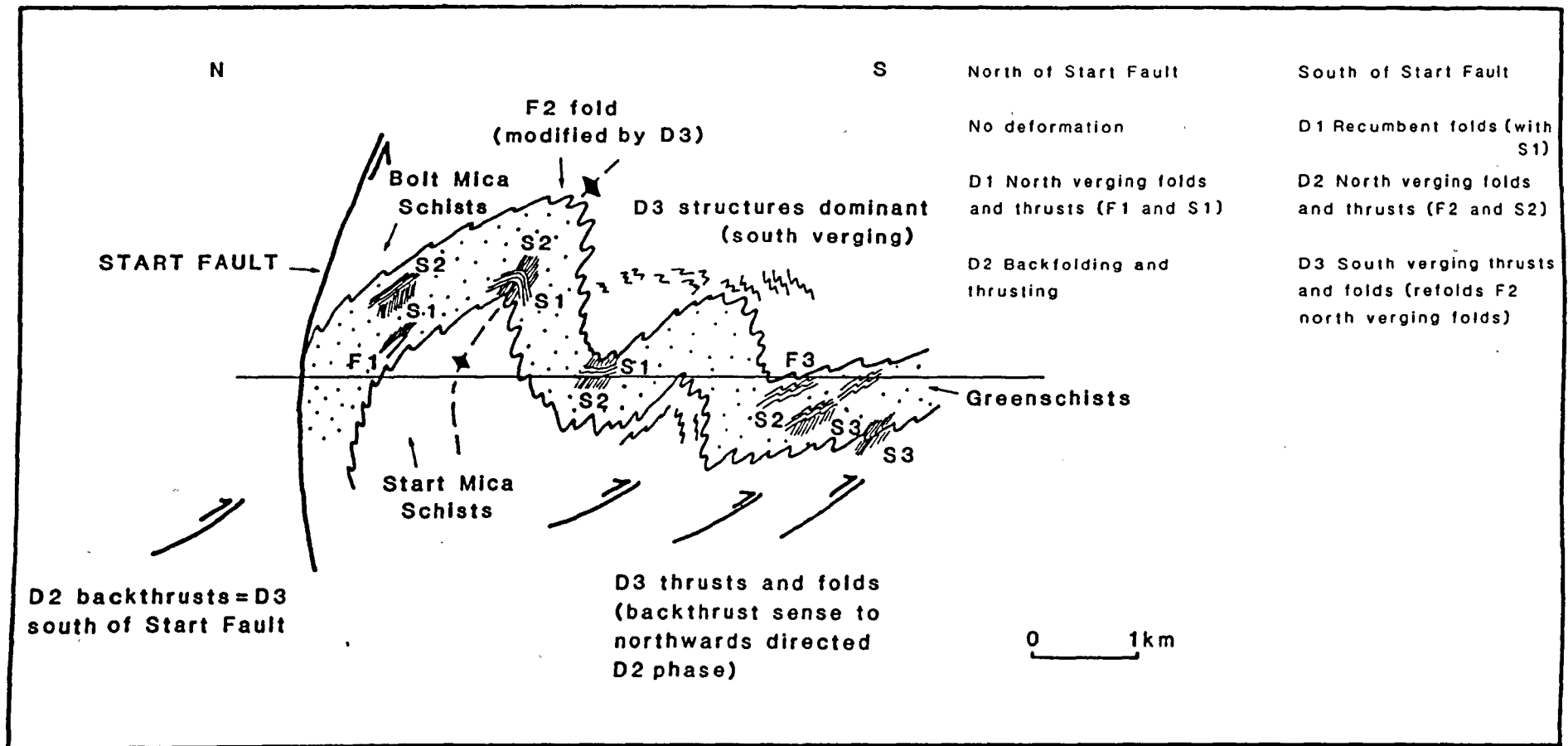


Fig. 5.1 Cross section through the Start Schist Complex and correlation of structures with those on the north side of the Start Fault. Data for the Start Schist Complex obtained from Tilley (1923), Marshall (1965) and Hobson (1977).

recumbent, often isoclinal and transposed by subsequent deformation episodes. He describes an axial planar schistosity in the Quartz Mica Schists and a bedding schistosity in the Green Schists and more massive quartz schists. The D1 structures are re-folded by D2 which produces second phase folds with near vertical axial planes and an associated steep crenulation fabric. The D3 and D4 phases both produce sets of kink bands.

Hobson (1976a, 1977) describes D1 folds as being more common in the Green Schists in comparison to the grey schists (Quartz Mica Schists). They are described as isoclinal or recumbent structures with the majority overturned towards the north. Facing is indeterminable due to the scarcity of way-up indicators. Hobson (1977) also describes tectonic slides at the upper and lower boundaries of the Green Schists and infers that the upper unit of schists is the oldest and the lower unit is the youngest (based on conventional rules of thrust tectonics) (cf. Butler, 1982). This is dependent on the slides cutting up section in their transport direction. The D1 fabric described by Hobson (1977) is a planar schistosity of quartz and mica, within the grey schists, and an axial planar lineation of hornblende and epidote in the green schists. Hobson (1977) states that the attitude of the D2 folds changes locally from being steeply inclined to almost recumbent. Minor D2 folds occur on the limbs of the major D2 folds and are overturned to both the north and the south. More recently, Coward & McClay (1983) discussed the timing of deformation in the SSC. They concluded that the dominant structures are steeply inclined and southward verging F3 in age and occur in both the SSC and the slates to the north. They also mention that the D2 antiform (Marshall, 1962; Hobson, 1977) results from earlier fold phases.

5.3 CORRELATION OF FOLD PHASES ACROSS THE START FAULT

In this section the deformation history of the rocks to the north (Slate Belt) and south (SSC) of the Start Fault is described. Firstly, the deformational history of the Start Schist Complex is addressed and is based on an assessment of previous work (referred to above) and observations made during this study. Secondly, the deformational history of the Slate Belt to the north of the SSC is presented and this is based on data from the present study.

D1 SSC: Recumbent or isoclinal folds which possess a sub-horizontal axial planar schistosity defined by quartz and mica grains (Quartz Mica Schists) and an alignment of hornblende and epidote (Green Schists). Northward directed slides occur at the Green Schist unit boundaries. Overall movement direction is to the north. Compartmental strike slip faults

form in association with the above structures.

D2 SSC: North and south verging parasitic small to medium scale folds with an axial planar crenulation cleavage. Axial planes and hence the D2 foliation are predominantly steeply inclined but their attitude changes locally. Folds (eg. $6^{\circ}/256^{\circ}$) verge to the north (overall transport direction). Thrusts, which are occasionally associated with the asymmetric folds, dip to the south. The Start Fault moves during D2 having formed initially as a thrust fault. This fault also shows evidence of strike-slip movement. The westerly plunging fold defined by the Green Schists on the BGS sheet 356 is a D2 antiform.

D3 SSC: Overall transport direction is to the south. D3 folds are asymmetric and verge to the south. These folds possess a north dipping, axial planar fabric which locally crenulates the D2 foliation. Folds of the same geometry deform the D1 fabric and locally appear to be D2 in origin when the true D2 fabric is absent. Thrusts are directed to the south and dip moderately towards the north.

D4 SSC: D4 is represented by a series of kink bands.

The above sequence of events can be compared with that recorded by the structures to the north of the Start Fault in the lower grade Devonian slates. Although the deformation phases are labelled D1-4 with D4 occurring at a later time than D1, they all form during one major phase of deformation.

D1 SLATE BELT: Mesoscopic and macroscopic asymmetric folds (eg. $10^{\circ}/255^{\circ}$) verge and face towards the north. A penetrative axial planar fabric occurs in the mudrocks (slaty cleavage) and a spaced cleavage is present in the sandstones. Thrusts are associated with some of the folds and their attitude varies along the section, steepening from flat-lying to vertical in a southwards direction. This is attributed to back steepening during foreland propagation of thrusts (D3). Compartmental faults form in association with the above structures. Slip vectors are generally SE plunging (eg. $30^{\circ}/148^{\circ}$).

D2 SLATE BELT: Synchronous with the D1 phase are localised areas of second phase (D2) folds of the slaty cleavage. These folds (eg. $11^{\circ}/228^{\circ}$) display a sub-vertical axial planar crenulation fabric. Their geometries indicate northwards transport.

D3 SLATE BELT: Back steepening of the structures in the south by thrust stacking gives rise to a suite of structures. Folded cleavage (eg. $02^{\circ}/230^{\circ}$), north dipping cleavage and north dipping, low angle faults and fractures occur in the south. These are not present in the area of flat-lying structures in the north.

D4 SLATE BELT: Kink bands appear to represent the final stages of deformation.

In this piece of work, the D2 deformational phase affecting the SSC is correlated with the D1 phase to the north of the Start Fault (Slate Belt). There seems to be no counterpart to the D1 (SSC) in the slates. Hobson (1977) agreed with Marshall (1962) in that the D1 phases should be correlated across the Start Fault, however, Marshall (1965) decided that it should be the D2 of the SSC which is equivalent to the D1 of the slates. From the review carried out here it is assumed that D3 (SSC), the southwards directed event, correlates with the D3 event in the slates. It then follows that D1 of the slates probably correlates with the D2 event in the SSC as they both represent major northwards directed movements. Hence the D1 phase in the SSC is an early feature which generated the schistosity, recumbent and isoclinal folds and slides. The SSC would have been emplaced during D2 thrusting. The structures produced during D2 are co-axial to the early phase (D1, SSC) but they also re-fold some of the D1 (SSC) structures. The Start Fault is thought to be an expression of D2 (SSC) thrusting later steepened by D3 (SSC and north). D2 (north) is a local phenomenon and cannot be correlated on a regional scale.

5.4 THE START FAULT BOUNDARY

The northern limit of the SSC is an E-W trending lineament separating the Start Schists from the Lower Devonian slates to the north. The boundary between the slates and schists is sharp and a gradation from one to the other does not occur. The boundary is therefore tectonic. The outcrop pattern is straight over a distance of ca. 16km suggesting that it is steep to sub-vertical in profile. This is also indicated by the steep attitude of bedding and cleavage on both sides and immediately adjacent to the fault. Fault geometry and its characteristics can be examined at the coast in the west near Bolt Tail [SX 6700 3975] (Pl. 5.1) and in the east near Hallsands [SX 8175 3900] (Pl. 5.2). The Start Fault is not a single tectonic break but a series of faults giving rise to a banded zone which comprises a series of slices of schist and slate. Both non-foliated and foliated breccias are present in the coastal

Plate 5.1 The Start Fault zone (sub-vertical) at Hope Cove [SX 6750 3980]. Looking west.



Plate 5.2 Faulting (north dipping) in the Start Fault zone at Greenstraight [SX 8180 3900]. Looking west.

sections which expose the fault (Pls 5.3 and 5.4).

The Start Fault, initiated during D2 (SSC), is modified by the D3 backthrusting event (north). The effect of this phase of southerly directed movement is to modify the attitude of the fault. The shape of the major D2 fold in the SSC is also affected. Interpretation of the evolution of the fault is complicated by the presence of small scale structures indicating strike slip movement in the fault zone. These occur in the form of E-W oriented shear bands (Pl. 4.58) which indicate dextral motion in a horizontal plane. They are observed at Outer Hope [SX 6750 4015] and similar structures are also observed in the slates just north of the boundary at Greenstraight [SX 8175 3900] (Pl. 5.5). The latter displace both first and second phase cleavages.

The present attitude of the boundary is sub-vertical in the west (Outer Hope) and north dipping in the east (Greenstraight). This north dip is probably a function of back steepening of a previously south dipping thrust fault (cf. Coward & McClay, 1983).

5.5 LARGE SCALE STRUCTURE OF THE START SCHIST COMPLEX

Ussher (1904) considered the structure of the SSC and concluded that the rocks were distributed about a synclinal structure. Tilley (1923) concluded that the main structure of the SSC is represented by a macroscopic anticline with the lower and older Start Mica Schists occurring in the core of the fold. Marshall (1965) shows that it is a product of D2 re-folding of an early schistosity and describes the fold as being antiformal. Hobson (1977) disagrees with Marshall (1965) that all the D3 structures are of kink band origin and he states that many are recumbent folds possessing a flat lying D3 crenulation cleavage which locally displaces the D2 fabric. These D3 structures verge towards the south. This suggests the occurrence of a backthrusting event when compared to the northward verging D1 and D2 structures of the SSC (see also Coward & McClay, 1983).

Three possibilities exist (after Marshall, 1965):

1. The SSC represents a primary recumbent structure with an antiformal core of green schist within a Quartz Mica Schist envelope.
2. The SSC represents the lower limb of a northward closing recumbent antiform leaving the Start Mica Schists (Tilley's lower unit) as the stratigraphically higher unit.



Plate 5.3 Non-foliated fault breccia along the fault surface shown in Pl. 5.2.



Plate 5.4 Foliated fault breccia along the Start Fault at Hope Cove (see Pl. 5.1).



Plate 5.5 Dextral shear bands in the Meadfoot Group rocks north of Hallsands [SX 3875 8180] displace both first and second phase cleavages. Looking north.

3. The SSC represents the upper limb of a northward closing recumbent antiform (leaving Tilley's stratigraphy unaltered ie. the Start Mica Schists are the oldest unit).

Marshall (1965) discards the first option due to the lack of factual evidence and concludes that the primary movements (D1 of the SSC) folded a sandwich of green schists between the Quartz Mica Schists into a northward closing recumbent antiform. He favours the third option although much of the evidence is inconclusive (Marshall, 1965 p. 330). With this in mind there seems to be no reason to object to the stratigraphy proposed by Tilley (1923).

5.6 A POSSIBLE STRATIGRAPHICAL CORRELATION FOR THE START SCHIST COMPLEX

The ideas put forward in this section are aided by the work of Marshall (1965). His data alone indicates the original lithologies, possible environments of deposition and the age of the SSC. When combined with the data of this project a broader correlation with the Lower Devonian sequence is attempted.

It has long been recognised that two rock types exist in the SSC, grey schists (Quartz Mica Schists) and Green Schists. From information on the BGS sheet nos 355 and 356 the thickness of the green schists is ca. 600m. The boundaries are modified by slides but the overall stratigraphy is not inverted (see above and Marshall 1965, p. 271).

The lower Quartz Mica Schists (Start Mica Schists) are deformed sandstones, mudrocks with occasional volcanics (Marshall, 1965), and the upper Quartz Mica Schists (Bolt Mica Schists) are also altered sandstones and mudrocks but, on the whole, are coarser (sandstones coarser and greater in number). The latter contain no volcanics except at the base, where the transition from Green Schists in the form of composite schists occurs. This unit is rich in pyrite.

The age of the SSC has always caused great debate, however, Marshall (1965, p. 450) indicates a probable Devonian age. As the Devonian sequence to the north of the complex ranges in age from Siegenian to Fammenian, with all stages represented, it may be argued that a counterpart for the SSC exists here. However, the base of the Siegenian and the Gedinnian stage are absent. Ussher (1904) suggested that a correlation be made with the Upper Devonian sequence around Plymouth which has thick sequences of volcanics in fine clastics. Although not proven by this study a possible equivalent to the SSC may occur within

the Dartmouth Group (see Fig. 5.2).

The Dartmouth Group is a succession of mudrocks and sandstones (metamorphosed to lower green schist facies altering the mudrocks to slate) ca. 3600m thick. Volcanics (air fall deposits) are present between an upper unit and lower sequence of clastics. The formation containing the volcanics is ca. 300m thick. The upper unit overlying them is on the whole coarser than the formation below the volcanics and there are relatively more sandstones which tend to be slightly coarser. Pyrite is abundant in the volcanic formation and in the clastics above but totally absent below (as with the SSC). Volcanic horizons can be found immediately above and below the volcanic formation forming transitional contacts. These observations on primary features are consistent with those observed in the SSC. The Bolt Mica Schists are therefore correlated with the Warren Formation, the Green Schists with the Yealm Formation and the Start Mica Schists with the Wembury Formation. The difference in thickness between the Green Schists and the Yealm Formation may be a function of their spatial relationship prior to Variscan shortening. Problems with this model do exist, the most obvious of which is that if these are laterally equivalent to each other then it is difficult to explain their contrasting metamorphic grades. One possibility is that the SSC represents locally metamorphosed Lower Devonian crust which has subsequently been emplaced and deformed (Coward & McClay, 1983; Dineley, 1986).

The suggestions made are based on tentative evidence and are speculative. However, they are made in order to stimulate interest and further research into their origin which is beyond the scope of this study. If the suggestions made are correct then the stratigraphic order given to the SSC by Tilley (1923) and Marshall (1965) is maintained.

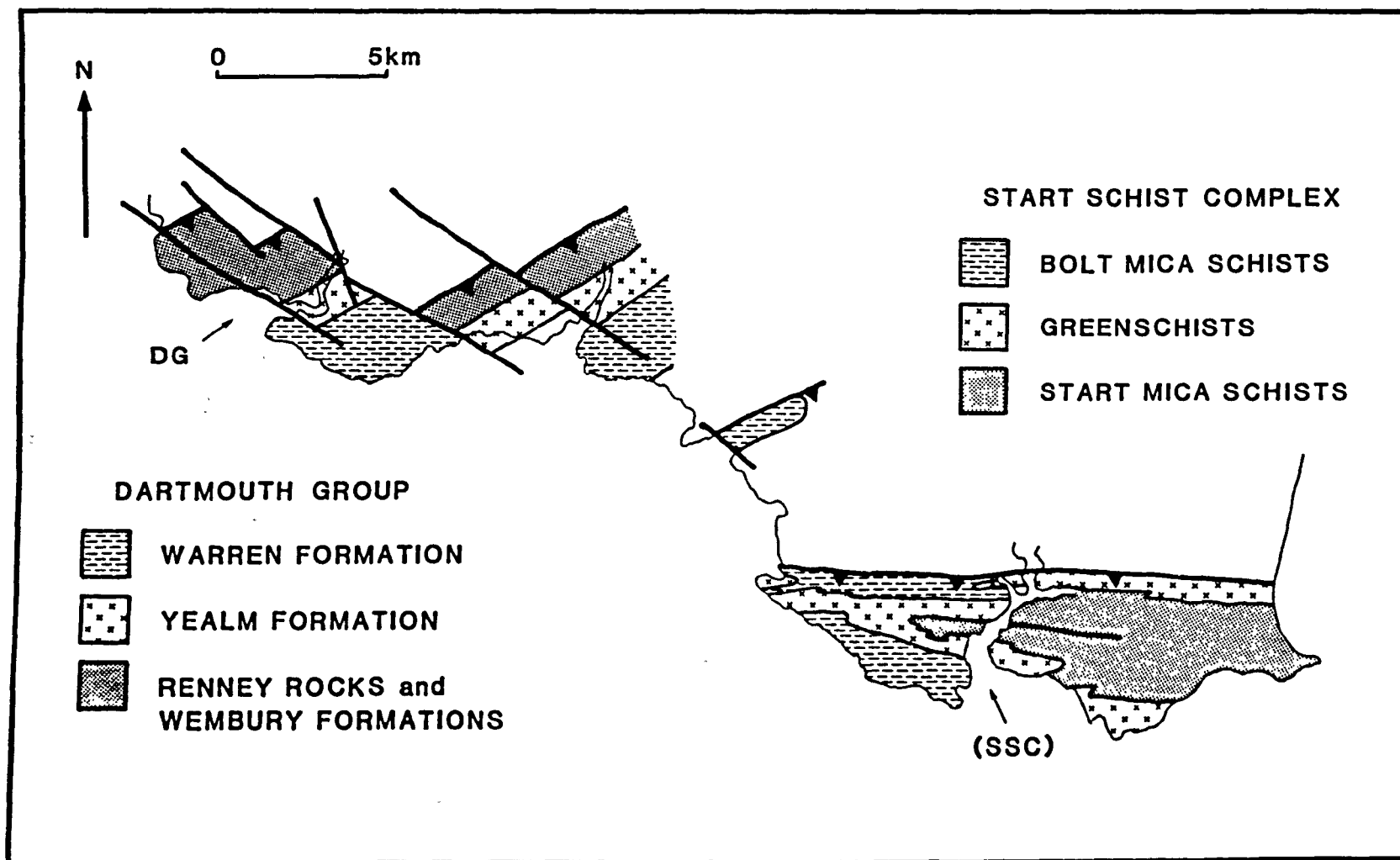


Fig. 5.2 Map showing the possible stratigraphical correlation between the Start Schist Complex and the Lower Devonian Dartmouth Group.

CHAPTER 6

POST VARISCAN EXTENSION AND BASIN DEVELOPMENT

New Red Sandstone (NRS) sedimentary basins are extensive offshore Plymouth and further south in the SW Approaches (BIRPS & ECORS, 1986; Ziegler, 1987; Chapman, 1989) and are associated with extensional systems which re-activate Variscan thrusts (Hillis & Day, 1987). The sedimentary and stratigraphic significance of the onshore extension of these basins in the Plymouth area is considered in Section 2.4. In this chapter the small scale structural features associated with the NRS deposits and post-Variscan extensional basin development are presented. The form of the Tertiary Basins is also considered in view of their similar distribution to the NRS basins and close association with pre-existing Variscan structures.

Along the coast between Plymouth and Bolt Tail many extensional faults, assigned to a post-Variscan phase of deformation, are observed and cut a deformed Devonian sequence. Their trends are variable but in general E-W and NE-SW oriented faults are dominant. The faults dip to the south or south east and are generally downthrown on their southern blocks. Both planar and listric faults are observed at outcrop scale. Planar faults ($045^{\circ}/40^{\circ}\text{SE}$) re-activate pre-existing cleavage planes and displace pre-existing thrusts (see Pl. 4.44). Displacements vary from a few cms to tens of metres across the minor scale faults. Fault gouges are commonly associated with the post-Variscan faults. In some cases the late faults re-activate pre-existing thrusts. For instance at Warleigh, north of Plymouth, the thrust fault which separates the Compton Slate Formation and the Saltram Slate Formation is re-activated by minor extensional fractures which detach into it (see Fig. 4.26). Similar features occur at Hopes Nose in the Torbay area. Here Variscan thrusts, which deform Devonian limestones, are both cut and re-activated by later extensional faults and the latter curve downwards into them (Fig. 6.1 and Pl. 6.1).

The above mentioned structures are not associated with NRS sequences. However, faults with associated NRS deposits occur at Thurlestone [SX 6760 4190]. One such fault at this locality is oriented E-W ($083^{\circ}/\text{sub-vertical}$) and is downthrown to the south. Some of the NRS sequences in the Plymouth area also have a close association with the pre-existing Variscan compartmental faults and thrusts (eg. at Crownhill Bay and Kingsand). It is likely therefore that these structures are re-activated during NRS extension and basin formation. The pre-existing orientation of structures and an approximate N-S extension direction during the Permian would mean that ca. E-W oriented thrust faults would re-activate as normal faults,

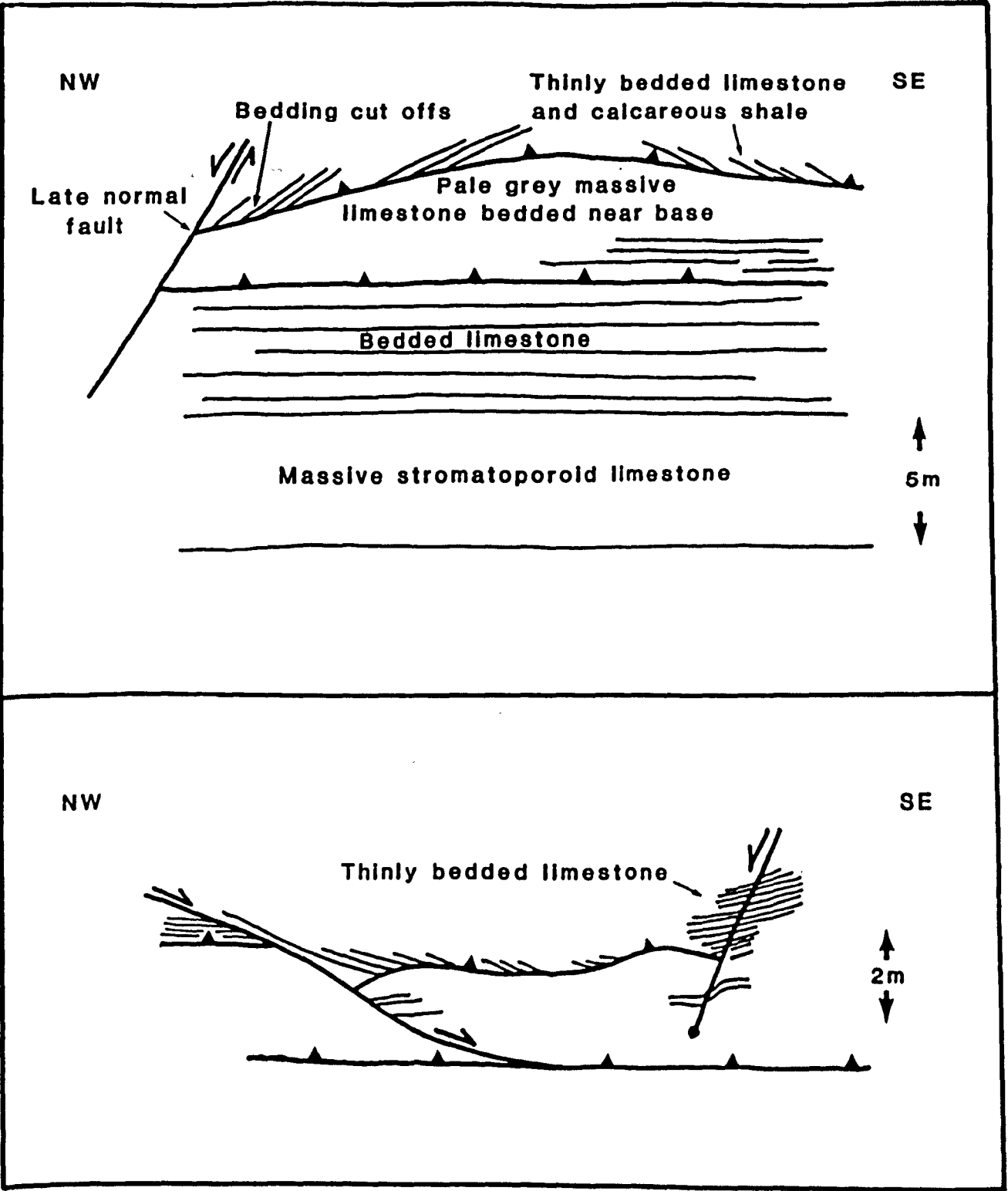


Fig. 6.1 Field sketches showing that late extensional structures both cut and reactivate pre-existing Variscan thrusts. Devonian Limestone, Hope's Nose [SX 9480 6370] near Torquay.



Plate 6.1 Post-Variscan extensional fault (low angle and listric) re-activating a Variscan Thrust; Hopes Nose [SX 9480 6370], near Torquay. Looking south west. Height of photograph ca. 4m.

with essentially dip-slip displacement, and compartmental faults (oriented ca. NNW-SSE) would become extensional transfer (or tear) faults, with components of oblique slip (Fig. 6.2). Under this regime large scale Variscan structures may also behave as bounding faults to the distribution of the NRS offshore basins eg. Plymouth Bay Fault (Figs 6.3 and 6.4). Both dextral and sinistral displacements will result across the NNW-SSE trending transfer faults.

The outcrop pattern and sub-surface distribution of Tertiary basins indicates their close affinity with pre-existing Variscan NNW-SSE trending compartmental faults. Onshore examples include the Bovey Basin and the Petrockstowe Basin which occur along the Sticklepath/Lustleigh fault zone (Fig. 6.4). The offshore extension of this fault into the Bristol Channel area also contains a Tertiary Basin, the Stanley Bank Basin (Roberts, 1989).

The form of the Bovey Basin indicates that it has originated as a pull-apart basin by Tertiary sinistral strike slip re-activation of a pre-existing Variscan compartmental fault (cf. Holloway & Chadwick, 1986). This sinistral sense of movement on the faults is in contrast to the widespread dextral movements experienced during Variscan deformation. Re-activation in the form of Oligocene inversion is also reflected onshore in SW England in the form of strike-slip pull-aparts as described above (Ziegler, 1987).

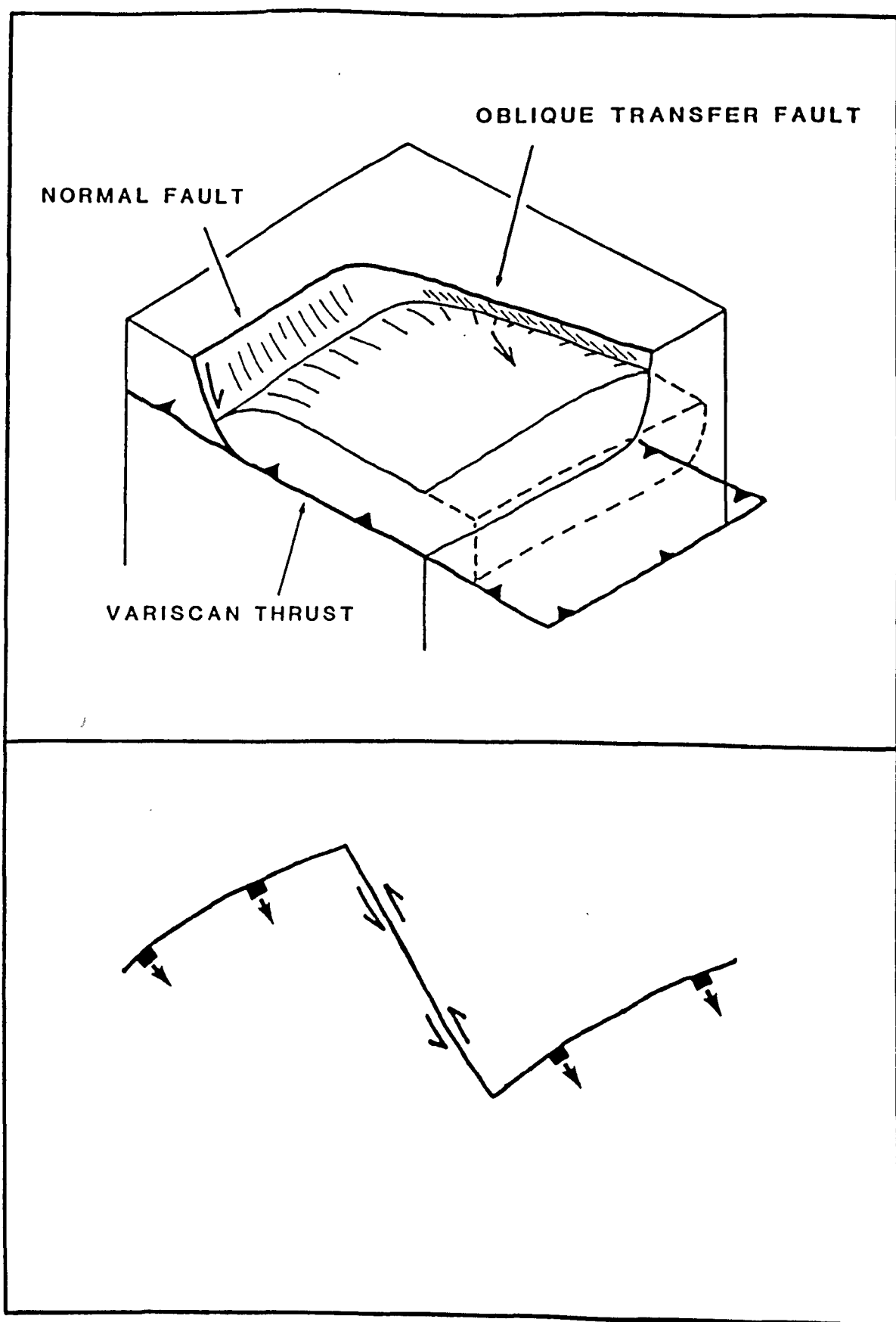


Fig. 6.2 Diagrammatic representation of an extensional fault system interacting with a pre-existing thrust fault (top). Plan view of a linked extensional fault system illustrating the sense of motion on the extensional transfer fault (bottom).

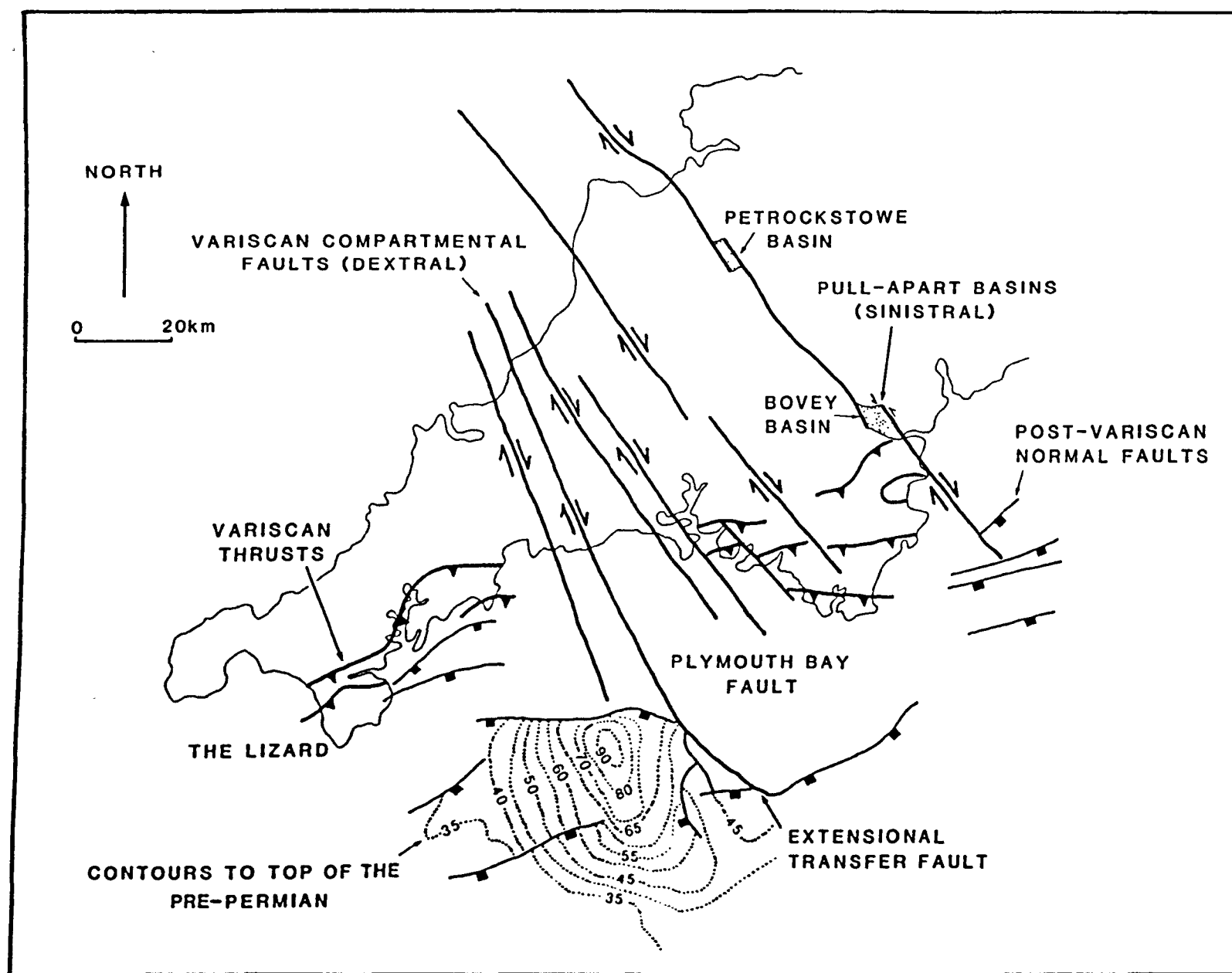


Fig. 6.3 Fault systems present onshore and offshore SW England illustrating their close association and regional trends. Contours to the top of the pre-Permian in the Plymouth Bay Basin are x100 m below sea level.

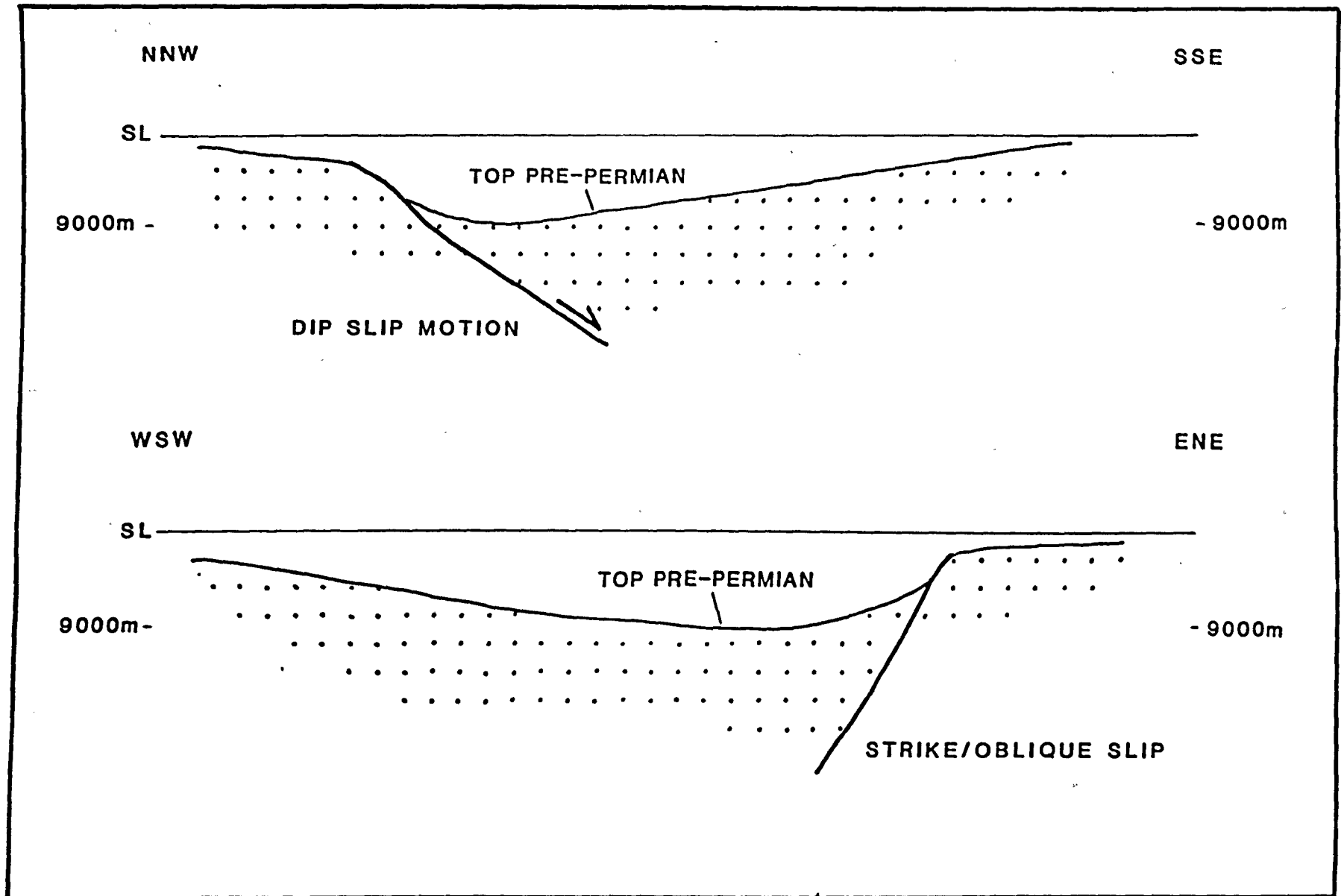


Fig. 6.4 Cross sections across the Plymouth Bay Basin.

CHAPTER 7

REGIONAL IMPLICATIONS

This chapter discusses the structural models applying to the study area of SW Devon and relates them to the regional tectonic regime of the Variscan of NW Europe. The structures of SW Devon are indicative of overall NW translation of Devonian and Carboniferous sequences by the process of thin-skinned tectonics. This is consistent with other areas in SW Britain (Shackleton, *et al.*, 1982), Ireland (Cooper *et al.*, 1984) and central Europe (Meissner *et al.*, 1981; Weber, 1981; Rast, 1988) where the structures are dominated by NW vergence and thrust transport. The above work has defined a belt of rocks, with similar structural styles, which extends from southern Ireland in the west through SW England to central Europe (France, Belgium and Germany) in the east. This belt of rocks comprises part of the external Variscides known as the Rheno-Hercynian (Autran *et al.*, 1980) (Fig. 7.1). Like SW Devon the metamorphic grade is consistently low, usually greenschist facies, across the belt. The northern margin of the Rheno-Hercynian zone is marked by the Variscan Front whilst to the south lies the Saxo-Thuringen zone consisting of higher grade metamorphic and crystalline basement rocks. The Saxo-Thuringen zone is also within the external Variscides and extends westwards from central Europe to Brittany and the SW Approaches. The internal Variscides lie to the south of the Saxo-Thuringen zone and extend eastwards from southern Brittany through France and Germany (Autran *et al.*, 1980).

The NW transport direction observed across the Rheno-Hercynian zone is oblique to a section of the Variscan Front between SE Ireland and Brussels but has a more orthogonal relationship in west Ireland and in central Europe, east of Brussels (Fig. 7.2). This obliquity and the presence of minor anomalous structures in SW Britain (cf. Shackleton *et al.*, 1982; Coward & McClay, 1983; Chapter 5) is consistent with, but not definitive of dextral transpressional models (cf. Max & Lefort, 1984; Sanderson, 1984). A dextral transpressional model for the evolution of the Variscides was put forward by Sanderson (1984). This is based on work in Ireland, SW England and Brittany. The Palaeozoic rocks of Brittany are characterized by steep folds and cleavage accompanied by a sub-horizontal stretching lineation and this is attributed to dextral shear (Gapais & Le Corre, 1980; Hanmer *et al.*, 1982). A transpressional model for the Irish Variscides is countered by the work of Cooper *et al.*, (1984) who prefer a thin-skinned model.

It is possible for transpressional structures to exist within a thrust belt (cf. Coward & Smallwood, 1984) although their occurrence is usually of minor importance compared with

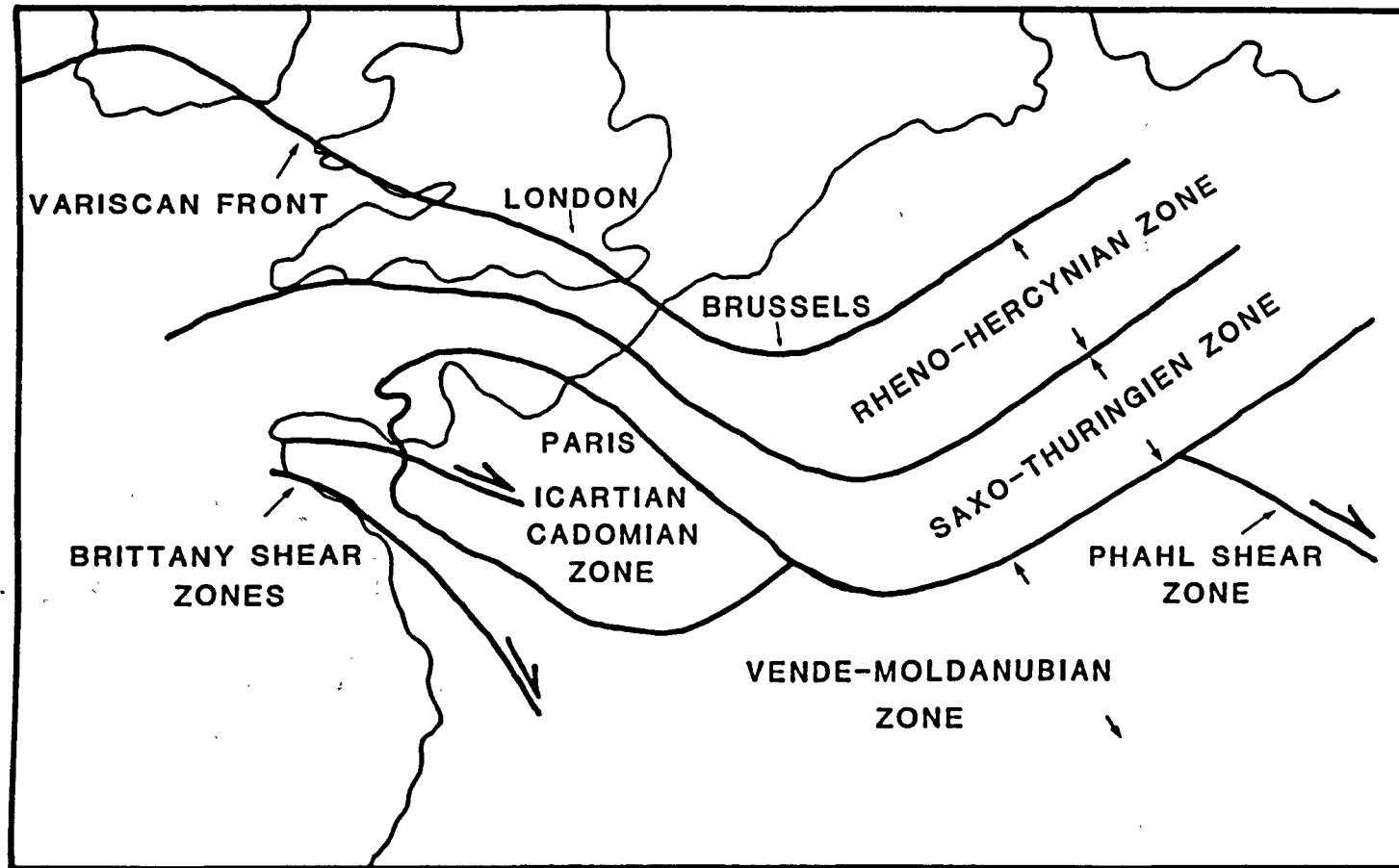


Fig. 7.1 Map of the Variscan zones of western Europe (after Autran *et al.*, 1980). Icartian and Cadomian zones form a microplate unaffected by Variscan deformation (see Coward and Smallwood, 1984).

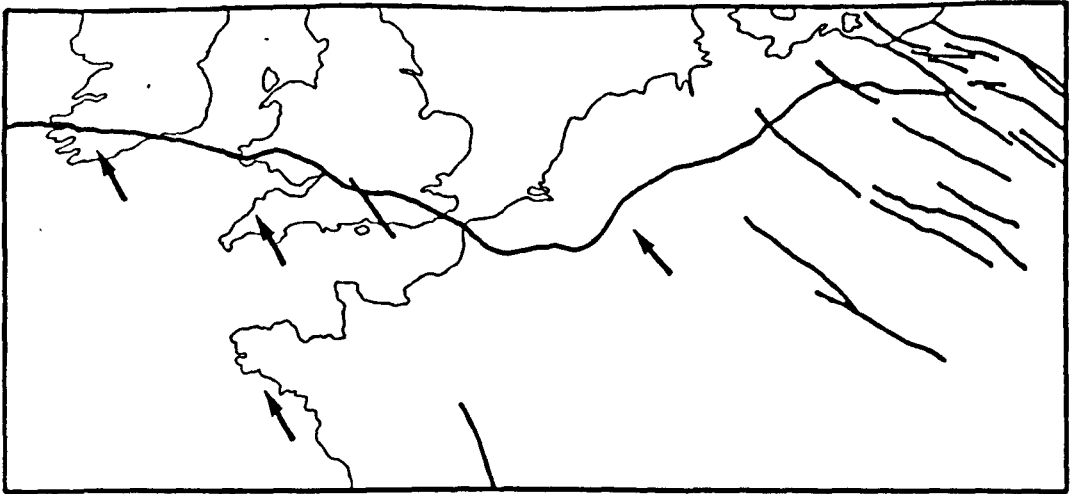


Fig. 7.2 Map showing the position of the Variscan Front in western Europe in relation to the regional transport directions. Note its oblique relationship through SW England (after Rast, 1988).

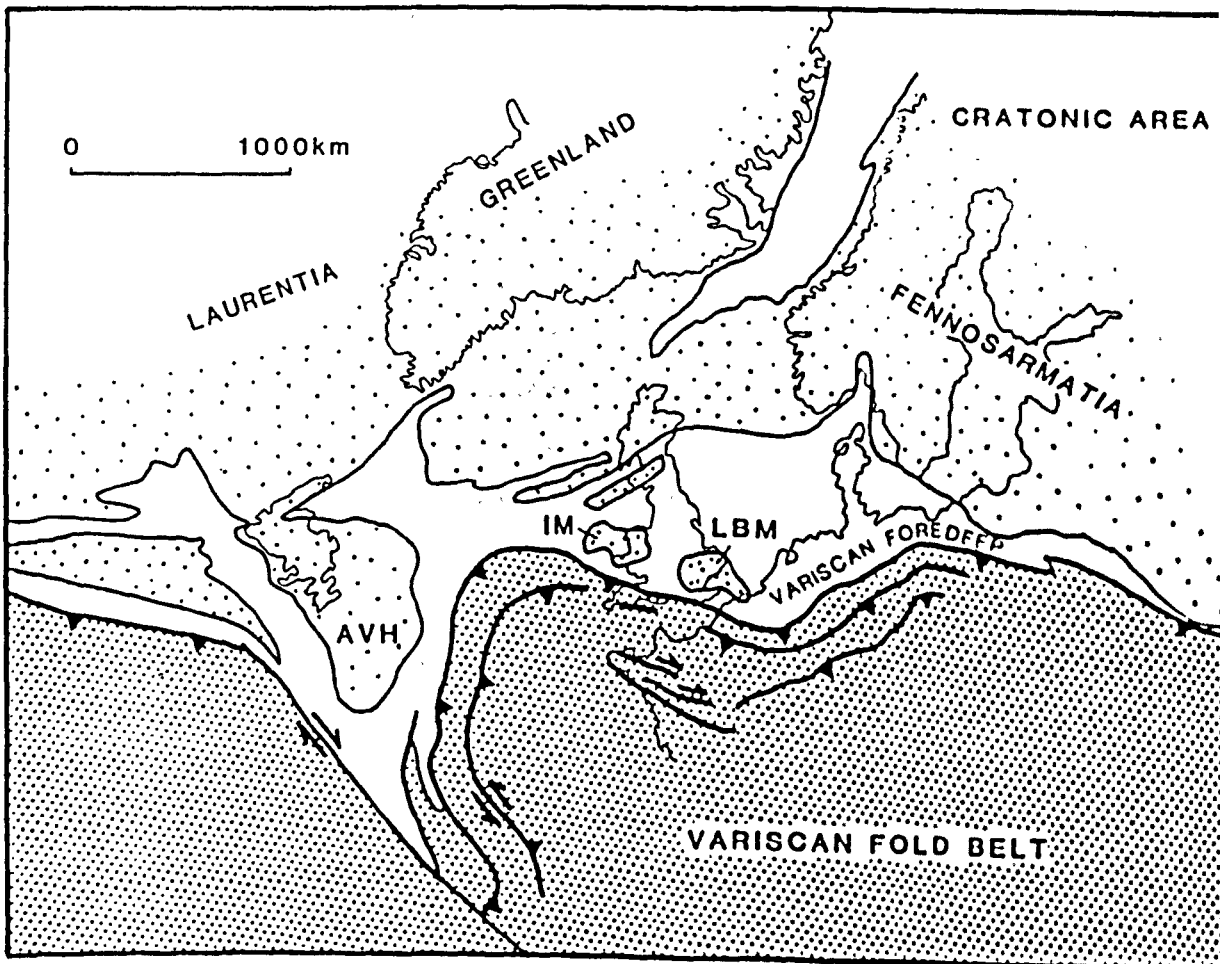


Fig. 7.3 Middle Carboniferous paleotectonic-paleogeographic map (after Ziegler, 1988). Note how the position of the cratonic blocks govern the shape of the Variscan Front. AVH, Avalon High; IM, Irish Massif; LBM, London-Brabant Massif.

the dominant thrust style of deformation. It is suggested in the present study that the dextral shear components within the Rheno-Hercynian zone, and associated with the Variscan Front, may be a function of conventional thrust tectonics. In this case the front between SE Ireland and Brussels, where it is oblique to the regional movement direction, behaves as a lateral structure (cf. Coward & Smallwood, 1984) and its position is controlled by the crustal form of the Variscan foreland (SW Laurentia). It is the position of the cratonic blocks (?microplates) referred to as the Avalon High, Irish Massif and London-Brabant Massif (cf. Ziegler, 1988) that in this case would control the position of the advancing Variscan Front (Fig. 7.3). These stable blocks control whether structures will form orthogonal to or oblique to the deformation front. It follows that structures forming along the front from SE Ireland to Brussels will be influenced by dextral shear but the dominant movement can still be one of thrusting to the NW. This is reflected by the arcuate trend of structures in southern Ireland (see Fig. 7.4) where they are deflected into the lateral zone. It also follows that maximum displacement will occur off the west coast of Ireland and in central Europe where movement is orthogonal to the thrust front. This fact has been noted by Cooper *et al.* (1984) who describes an increase in displacement between SE and central Ireland. This increase in displacement away from areas of obliquity is accommodated by compartmental faults such as those observed across SW England which all show dextral displacements. A hypothetical model for the above system is illustrated in Fig. 7.5. The above model is not unlike the indentation model applied to the style of deformation in eastern Asia (Tapponier *et al.*, 1985).

The relative width of the Rheno-Hercynian zone in central Europe is comparable to that in SW Britain and Ireland (Fig. 7.1). However, this is greatly reduced in northern France and southern Britain where dextral shear has taken place along the Variscan Front (Fig. 7.1). The southern limit of the Rheno-Hercynian zone in SW England is taken to correspond to the northern limit of the Start Schists which in turn may be equated with the quartzite-mica schist series of the mid-German crystalline rise in the region of northern Spessart (cf. Weber, 1984). The distance between the Start Schists and the Variscan Front is difficult to ascertain in SW Britain as the westward projection of the Start Fault, whether it corresponds to a splay off the Lizard Thrust or the Perranporth line, is difficult to predict offshore.

It is generally accepted that the Variscan belt of the North Atlantic region is complex and that the areas which comprise the belt show varying degrees and styles of deformation. Badham (1982) explained the lateral variability of the orogen in terms of an oblique collision model with a dextral interaction of the European (Laurentia) and African (Gondwana) continental plates. This model accounts for the presence of strike slip, contractional and

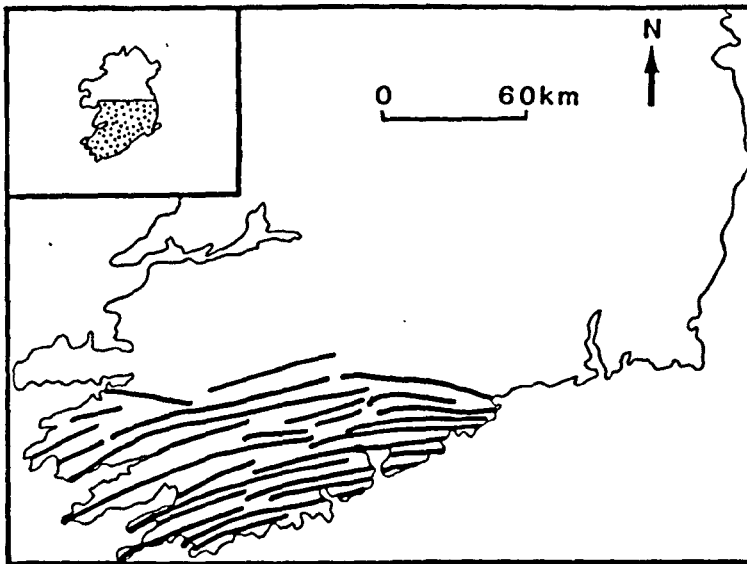


Fig. 7.4 Map showing the arcuate trend of Variscan structures in southern Ireland (after Max and Lefort, 1984).

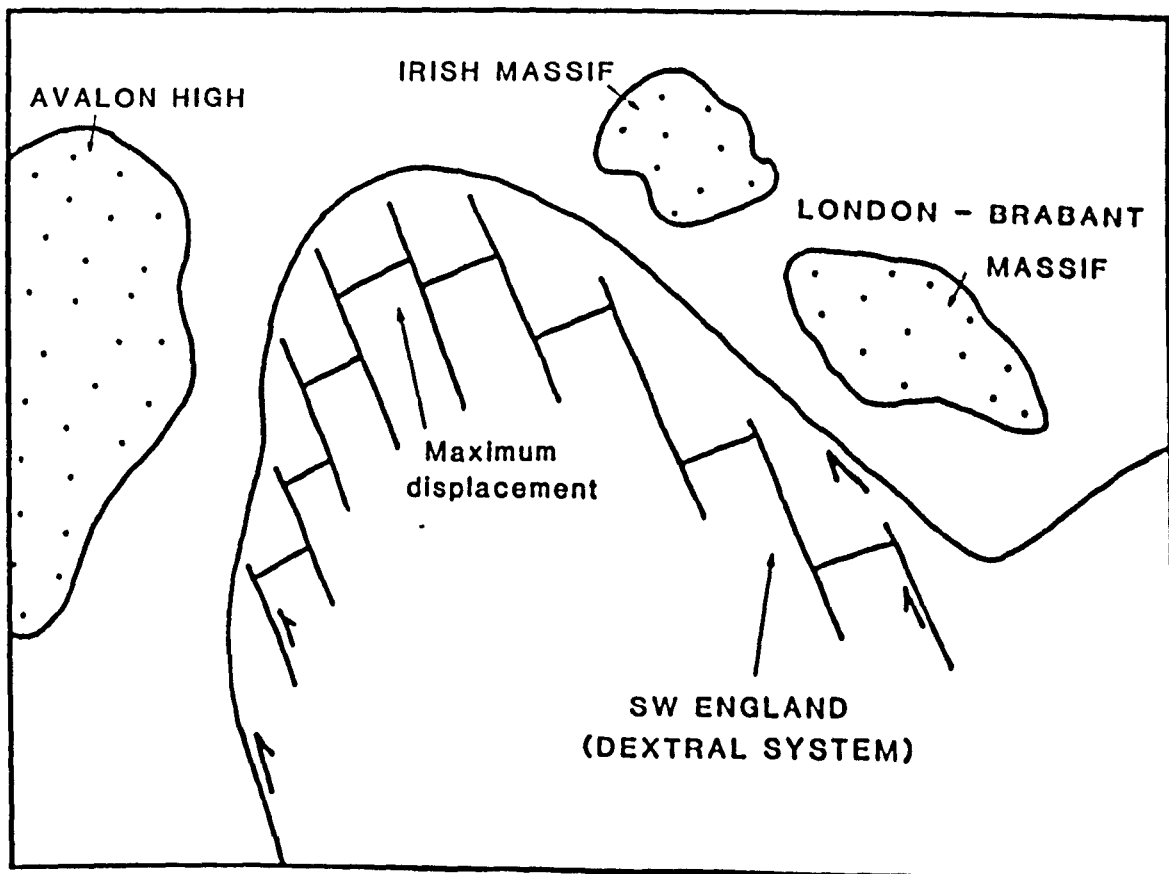


Fig. 7.5 Hypothetical model illustrating the association of the thrust and dextral compartmental fault system of SW England to the shape of the Variscan Front implied by Fig. 7.3.

extensional structures. This and other regional models is not challenged on the basis of the present new data obtained in SW England as only a detailed study of the whole Variscides would allow this and this is not within the scope of the present project. However, it is stressed that compressional thin-skinned tectonics are thought to dominate the Variscan of SW England and that dextral shear parameters observed in the study area, and elsewhere in SW Britain and Ireland, may purely be a by-product of SE-NW thrusting.

CHAPTER 8

GEOLOGICAL EVOLUTION

8.1 INTRODUCTION

This section describes the evolution of the SW Devon area from basinal deposition through subsequent deformation during the Variscan Orogeny. Comparison of its structural style and timing of deformation will be made with other areas in the European Variscides. The major aspects of the Devonian basins are described first (Section 8.2). This is followed by a brief summary of the tectonic style produced during the deformation of these basins and how subsequent sedimentary basins (Carboniferous) are generated and deformed (Section 8.3). Post-Variscan structuring, sedimentation and intrusive activity are also discussed (Section 8.4).

8.2 DEVONIAN SEDIMENTATION

The first record of sedimentation in SW Devon is shown by the rocks of the Dartmouth Group (Siegenian in age). They represent deposition on a distal, alluvial plain (Fig. 8.1). The lowermost unit (Renney Rocks Formation) is represented by a series of sheet flood deposits recording an initial pulse of coarse clastic sedimentation. Deposition of this unit probably resulted from tectonic uplift in the source area to the north. The overlying finer deposits of the Wembury Formation represent a more quiescent period of sedimentation. A sequence of marginal lake deposits (Yealm Formation) overlies the Wembury Formation and indicate drowning of the alluvial plain. The overlying Warren Formation marks a return to the distal, alluvial environment with the occurrence of periodic sheetflooding and more quiet periods of sedimentation. Thus the sequence shows evidence of pulsatory sedimentation interspersed with more quiescent periods which are probably direct responses to source area modifications. Drainage over the basin was NNE-SSW and along with the distal nature of the sediments indicates that the source area lay far to the north of SW Devon. The clastic sediments of the Dartmouth Group were probably deposited in basins above a rifted continental margin similar to that shown for the area further to the west (cf. Badham, 1982; Sanderson, 1984). This rifting is the most likely cause of the basic volcanism evident in the Devonian sequence of SW Devon. To the south the area was submerged and deposition took place in a shelfal sea which experienced intermittent volcanism (Badham, 1982). This open sea eventually transgressed across the SW England area.

The northward marine transgression over the alluvial plain sediments led to deposition of the

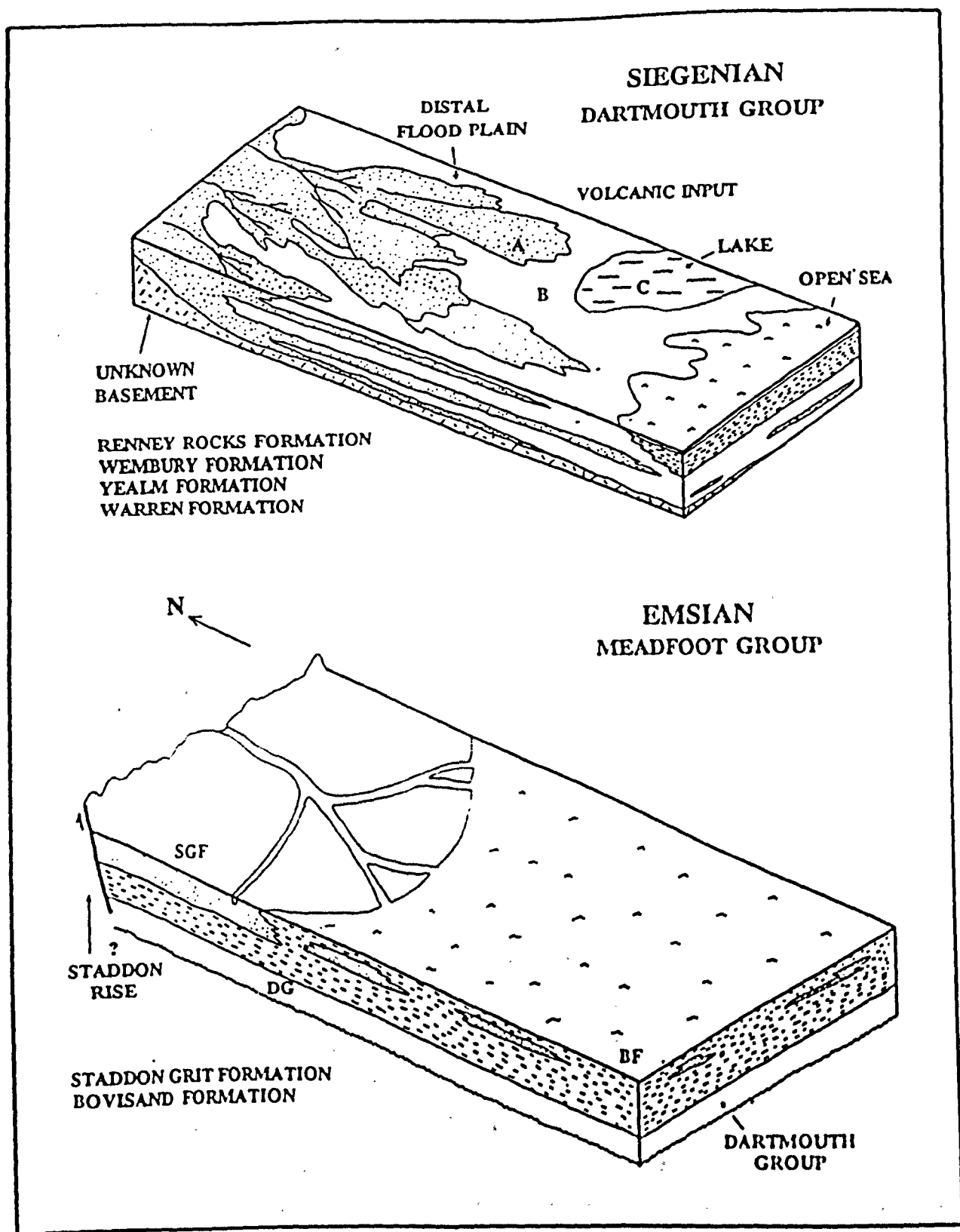


Fig. 8.1 (upper) Schematic model to show the depositional environments preserved in the Dartmouth Group rocks of SW Devon and the likely palaeogeographical setting. A - Renney Rocks Formation, B - Wembury Formation, C- Yealm Formation, A/B - Warren Formation.

Fig. 8.2 (lower) Schematic model to show the depositional environments preserved in the Meadfoot Group rocks of SW Devon and the likely palaeogeographical setting.

essentially Emsian aged Meadfoot Group (Bovisand Formation) on an open marine shelf (Evans, 1985; see also Selwood & Durrance, 1982 for alternative explanations). The Bovisand Formation passes laterally (to the north) and upwards into the Staddon Grit Formation (Fig. 8.2). This is a coarse clastic facies the petrography of which is dissimilar to that of the Dartmouth Group rocks (Pound, 1984). Hence, the origin of the Staddon Grit Formation is unlikely to be that of drainage of the alluvial plain sediments of the Dartmouth Group as suggested by Selwood & Durrance (1982). The Staddon Grit Formation, which represents a southward regressive pulse of sedimentation, is more likely to be controlled by the Staddon Rise (Hendriks, 1959; Pound, 1984) consisting of a faulted block of unknown age. Deposition off the Staddon Rise occurred in a fluvial dominated, low wave energy deltaic setting (Pound, 1984) which was highly constructive, lobate and had associated distributary mouth bars. The latter are represented by sequences observed at the boundary between the Staddon Grit Formation and the underlying Bovisand Formation. Further transgression/sea level rise over the area led to the development of marine shelf conditions and deposition of the Plymouth Group (Eifelian to Frasnian). Minor movement on fault blocks similar to that which produced the Staddon Rise may have led to the development of the Plymouth Limestone Formation (Fig. 8.3). This formation passes laterally into more basinal marine facies containing volcanics and limestones. Marine conditions continued into the Late Devonian (Famennian), with the deposition of the Saltram Slate Formation (Fig. 8.4), and Early Carboniferous sediments.

8.3 VARISCAN DEFORMATION

Emergence of the succession described above occurred during the advancement of the Bretonic landmass from the south (cf. Holder & Leveridge, 1986) and with the onset of Variscan deformation, in the form of thin-skinned tectonics (Fig. 8.5), in SW England (ca. 340-320 ma.) (Dodson & Rex, 1971). Structuring of this Devonian sequence in SW Devon and Cornwall is thought to result from collisional tectonics related to a southward dipping subduction zone located further south (Shackleton *et al.*, 1982; Holder & Leveridge, 1986). However, it is unlikely that the northern margin of the subduction zone was part of one ocean basin. It is more likely that a number of disconnected basins existed (Badham, 1982; Holdsworth, 1989). Northwards advancement of a deformation front, associated with this plate margin, across SW England, incurred 61% shortening in the area studied. This also led to the development of a foreland basin ahead of the deformation front consisting of Lower Carboniferous sediments (Fig. 8.6). With continuing northward transport of structures through the Palaeozoic rocks this foreland basin became underthrust by the Devonian 'slab' and in turn backthrust towards the south (Fig. 8.7). Deformation proceeded in a northwards direction to as far

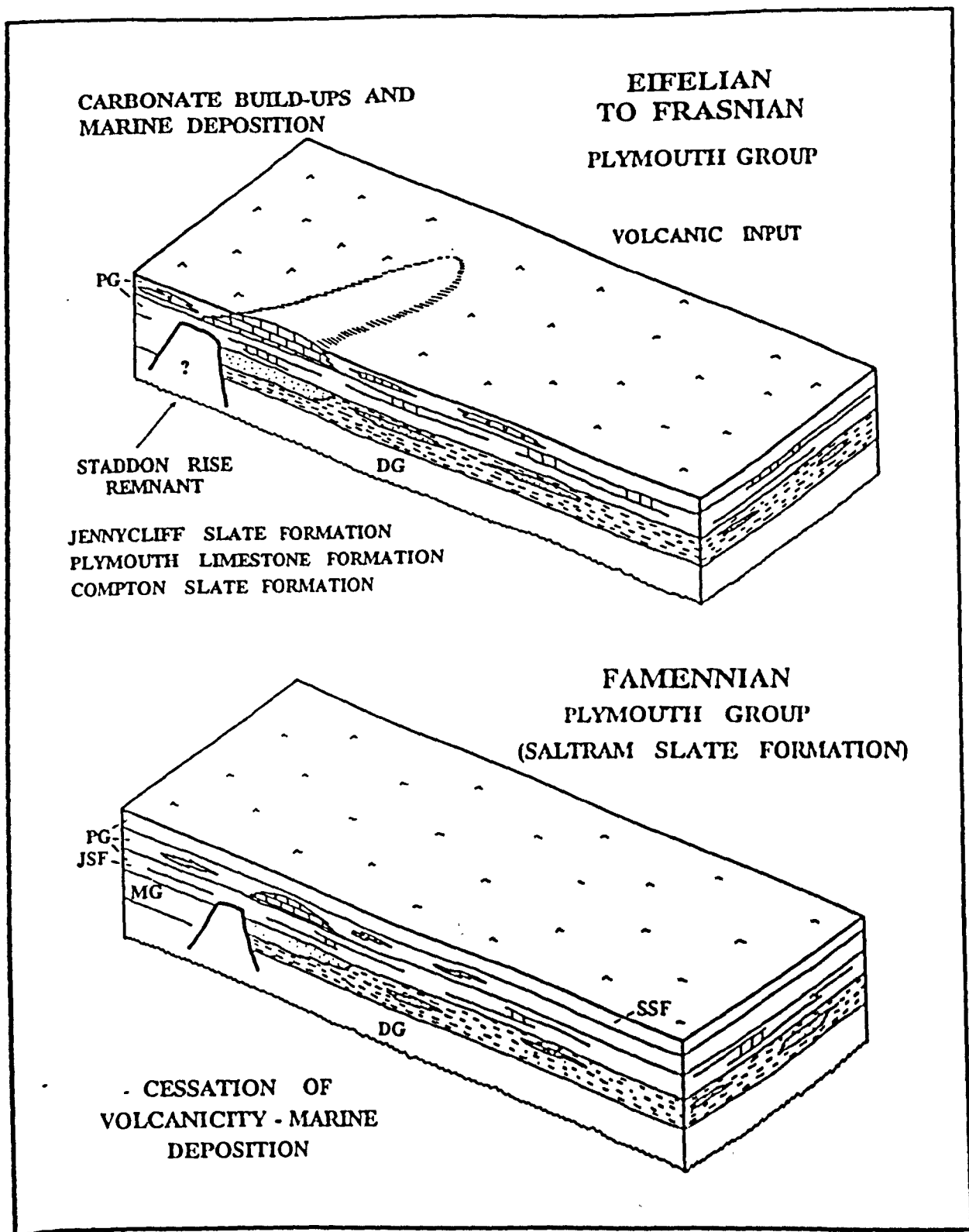


Fig. 8.3 (upper) Schematic model to show the depositional environments preserved in the Plymouth Group rocks of SW Devon and the likely palaeogeographical setting.

Fig. 8.4 (lower) As above for the Saltram Slate Formation of the Plymouth Group.

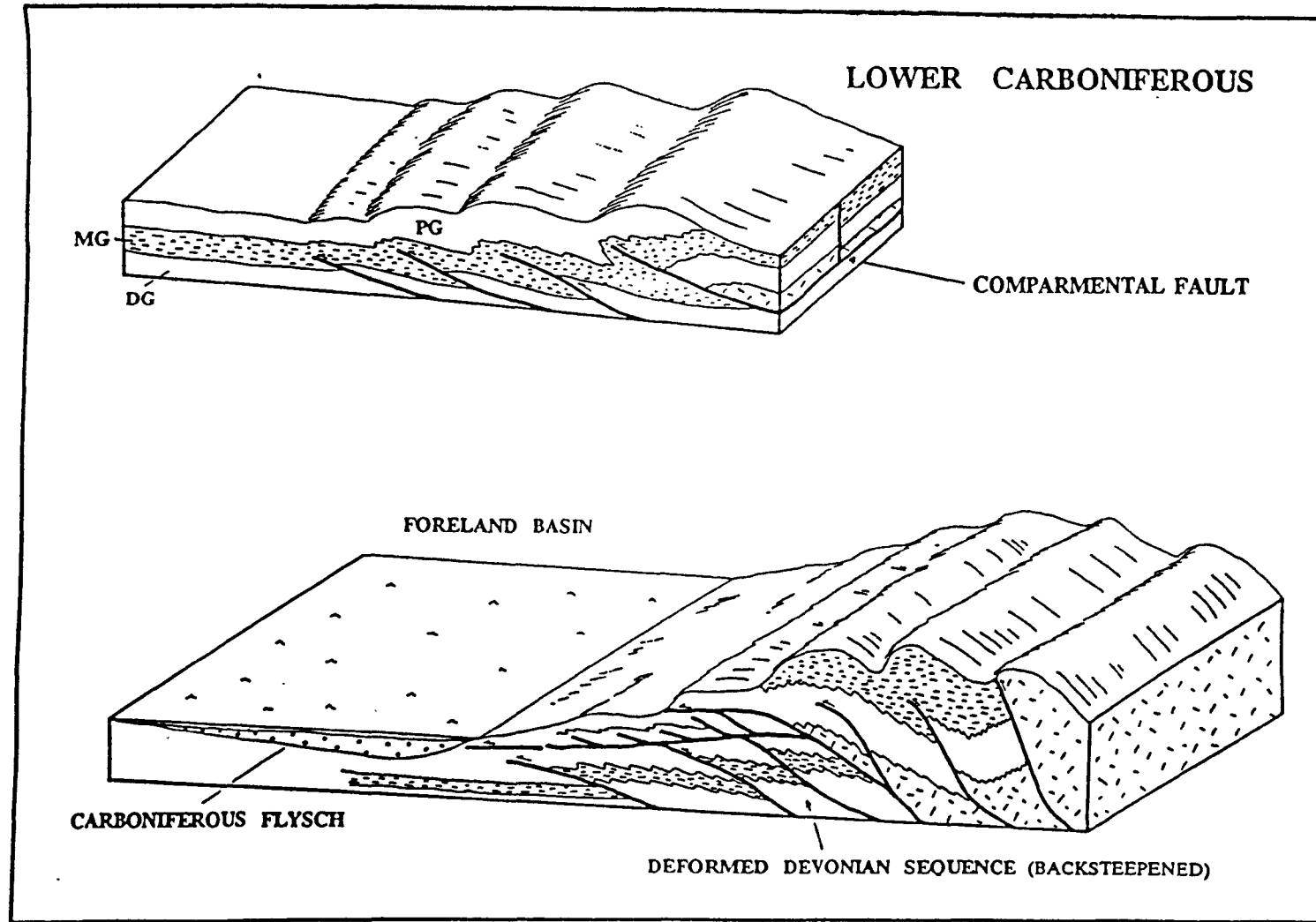


Fig. 8.5 (upper) Schematic model showing the initial thrusting of the Devonian sequence of SW Devon.

Fig. 8.6 (lower) Schematic model showing the Early Carboniferous deformation of the Devonian sequence and the initiation of a foreland basin in central SW England.

LOWER CARBONIFEROUS

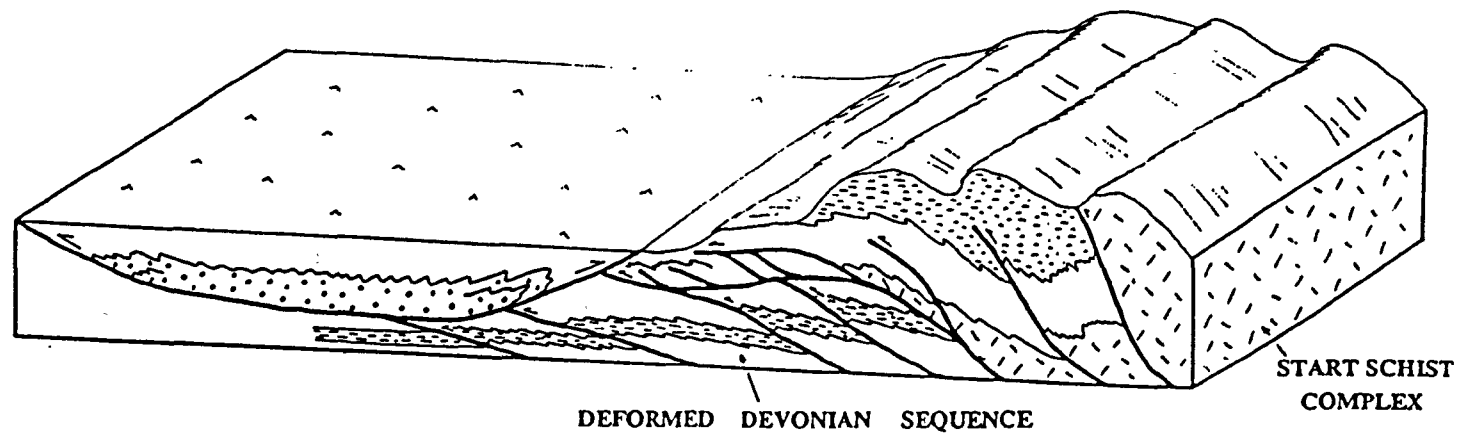


Fig. 8.7 Schematic model showing more advance deformation and how the northward moving deformed Devonian 'slab' interacts with the deforming foreland basin deposits.

as the present position of the Variscan Deformation Front (Fig. 8.8a) resulting in the internal deformation of the foreland basin deposits. The northern limit of the deformed Variscan in France occurs along the margin of the London-Brabant Massif (Raoult, 1987) which is consistent with the models presented in Chapter 7.

Structural styles in the section through the Variscan zone of SW Britain may be compared and contrasted with those in a cross section through the Rheinisches Schiefergebirge of western Europe (Weber, 1984) (see Fig. 8.8b). The two sections display very similar features; an increase in metamorphic grade to the SW, steepening of structures to the SW and the presence of flysch sediments sourced by uplift of the deforming Palaeozoic sequences to the SW. However, the geometry of the structures which deform the deformed flysch deposits (Giessen Greywacke in western Europe) are at variance to the structures associated with the underthrust model which is thought to deform the Carboniferous flysch deposits of SW England. In western Europe the Giessen Greywacke has supposedly a sedimentary source to its south and its subsequent deformation was driven by gravity sliding towards the north. This is not unlike the models proposed for the evolution of SW England presented in the works prior to the present study (Isaac *et al.*, 1982; Isaac *et al.*, 1983). In the Rheinisches Schiefergebirge erosion of the mid-German crystalline rise and turbidite deposition (Giessen Greywacke) in a basin on its northern margin began as early as lower Upper Devonian (Weber, 1984). In south Cornwall it has been suggested that deformation had begun further to the south in the Lower to Middle Devonian with deposition of the Gramscatho Group (Leveridge, *et al.*, 1984). Flysch sedimentation in the foreland basin of SW England implies that erosion of the uplifted, deformed Palaeozoic sequence took place during the Viséan (Isaac *et al.*, 1982). The age relationships of the various basins across the fold-belt are often directly related to the timing of deformation. It is clear that deformation started in the south and moved to the north through time, however, lateral variation may also occur.

Weber (1984) shows that the basement underlying the deformed Palaeozoic of western Europe consists of lithologies similar to those observed in the mid-German crystalline rise. In SW England the basement may consist of Devonian sediments older than the Siegenian ages observed in SW Devon i.e. rocks similar to the Gedinian Roseland Formation (volcanics, slates and quartzites). These may lie upon Proterozoic crystalline basement similar to that seen in western France. Alternatively the Dartmouth Group rocks may overlie a basement consisting of rocks similar in lithology to the Start Schist Complex. The Moho is thought to lie at around 30km depth in the region of both of the cross sections shown in Fig. 8.8 (cf. Dymant, 1990).

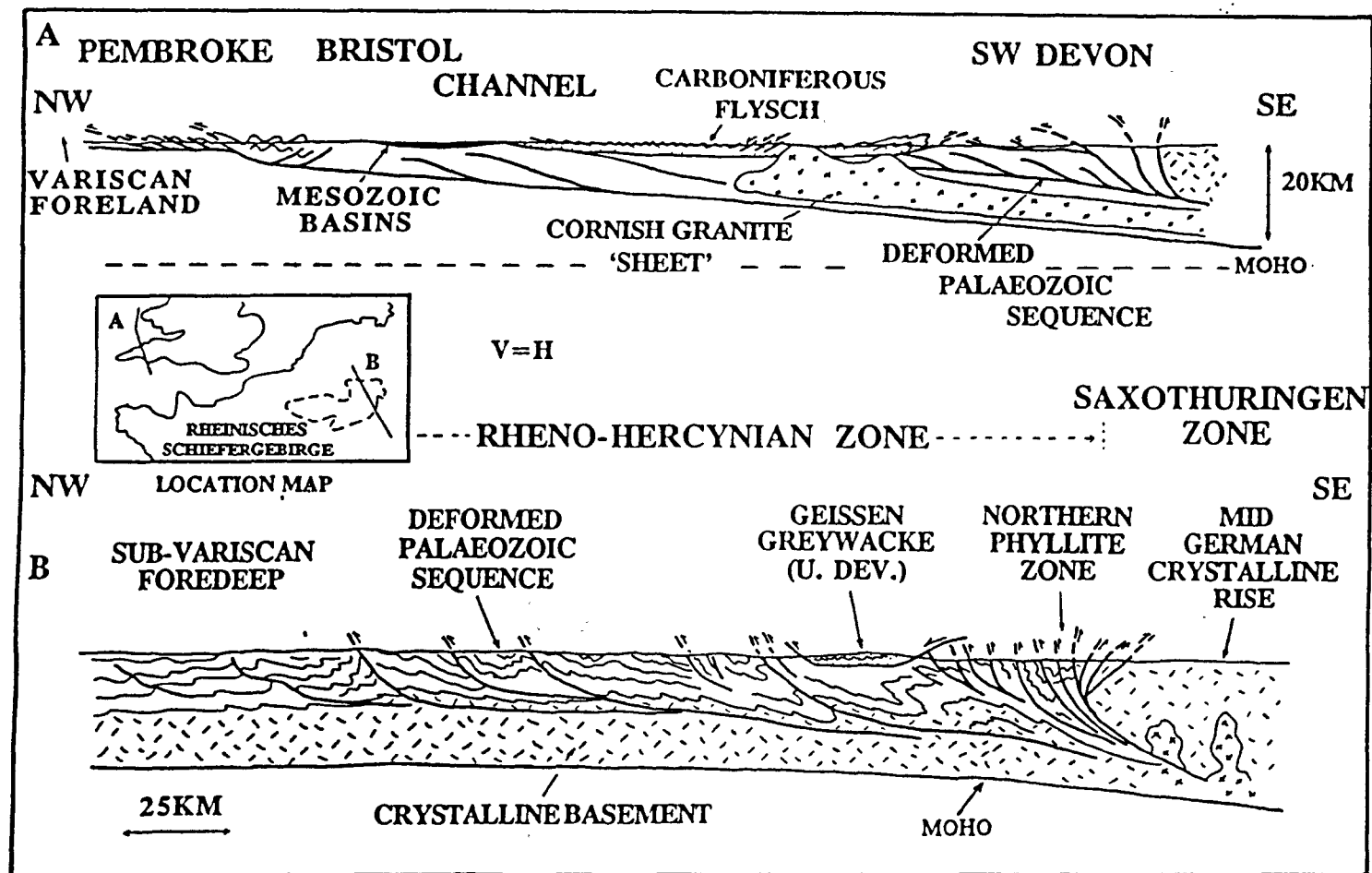


Fig. 8.8a (upper) Cross section across the Variscan Orogen of southern Britain from SW Devon to the Variscan Front in Pembrokeshire.

Fig. 8.8b (lower) Cross section through the Rhenisches Schiefergebirge of western Europe (after Weber, 1984).

8.4 POST VARISCAN ADJUSTMENTS

Variscan deformation was followed by a period of relaxation, extension, red-bed deposition and granite intrusion ca. Permian times.

Simpson (1979) suggested that the Cornish granites are Andean-type implying generation above a subduction zone. However, Dewey & Burke (1973), Mitchell (1974) and Mitchell & Garson (1981) favour a collisional model. A similar origin was proposed by Windley (1984) who compares the Cornish granites with those on the foreland of the Indian Plate in the Higher Himalaya. It was also noted by Shackleton *et al.*, (1982) that it is unlikely that the Cornish granites, which occur in a zone where the crust is in the region of 30km thick, were generated by crustal melting in a setting envisaged by Simpson (1979). The presence of a thin-skinned model (also proposed in this study) and the existence of a southward dipping subduction zone, south of the Lizard Complex (Shackleton *et al.*, 1982; Holder & Leveridge, 1986), does not support a crustal origin for the granites (Shackleton *et al.*, 1982). Thus the model in which the granites are injected northwards as a sheet intrusion from which individual granite masses have moved upwards diapirically by stoping to form the separate granite bodies which are now exposed is supported (cf. Shackleton *et al.*, 1982) (see also Fig. 8.8a).

Late stage events of the Variscan Orogen are also represented by N-S extension and associated red-bed deposition (New Red Sandstone). Extensive deposits occur offshore SW England in the Bristol Channel and in the SW Approaches (Zeigler, 1987) and more minor deposits are observed onshore in SW Devon. It is likely that many of the structures (normal and transfer faults) resulting from this extensional phase re-activated pre-existing Variscan thrusts and compartmental faults of similar trends. Some of the strike slip faults which are active in the Tertiary are also thought to be re-juvenated Variscan compartmental faults.

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VOLUME CONTAINS CLEAR OVERLAYS

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APPENDICES

APPENDIX 1 PUBLICATION RESULTING FROM THE THESIS

APPENDIX 2 SUMMARY MAPS OF THE MAIN STUDY AREA (see back pocket) (2 items)

APPENDIX 3 REPRODUCTIONS OF FIELD AND BASE MAPS (see back pocket) (31 items).

The confrontation of structural styles and the evolution of a foreland basin in central SW England

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Abstract: Detailed mapping of the rocks to the north and south of Plymouth reveals a sedimentary sequence deformed by a series of folds and thrusts. Two structural zones exist each with a different style of deformation. In the Lower to Upper Devonian rocks of the southern zone, slip vectors, vergence and facing of D1 folds indicate that the transport direction is to the north-west. An associated first phase cleavage dips to the south-east. The northern zone, of Upper Devonian and Lower Carboniferous strata, extends into central Devon and east Cornwall and the geometry and facing of the early folds in these rocks indicate a transport direction to the south or south-east. D1 folds generally verge north but are downward facing towards the south. A flat-lying, penetrative slaty cleavage occurs in the mudrocks and also indicates southward facing. Generally the Carboniferous rocks in this area are inverted. The two structural zones confront each other at an E–W-trending line which passes through Cargreen, 8 km north of Plymouth. Here the deformation is more intense as the cleavage, common to the southern zone, overprints that of the northern zone, resulting in the formation of D2 folds. The confrontation is interpreted as a northerly dipping backthrust produced by large-scale underthrusting. It is proposed that the northward-advancing Variscan thrust belt progressively underthrust the Carboniferous foreland basin flysch deposits which became inverted and backthrust towards the south.

For some years it has been accepted that a zone of south-facing D1 folds occurs in an E–W belt from Dartmoor to the north Cornish coast. These folds oppose the zone of northward facing first phase Variscan folds of south Devon and south Cornwall (Fig. 1). On the north Cornish coast these two contrasting zones of folding meet at what is known as the Padstow or Polzeath facing confrontation (Gauss 1967, 1973; Dearman 1970, 1971; Roberts & Sanderson 1971; Freshney *et al.* 1972; Sanderson & Dearman 1973; Hobson & Sanderson 1975, 1983; Sanderson 1979). Furthermore, Shackleton *et al.* (1982) and Coward & Smallwood (1984) explained the confrontation in terms of southerly directed backthrusting. The facing confrontation was projected eastwards to the area north of Plymouth (Sanderson & Dearman 1973, fig. 1; Hobson & Sanderson 1983, fig. 6.5) where southerly facing folds were recognized in the Okehampton, Lydford and Tavistock areas. Figure 1 shows the distribution of fold facing directions in central SW England observed by the authors and by those referred to above.

Subsequent to the work by the above authors a major geological mapping programme has been undertaken by a group from Exeter University, in part on contract to BGS, in central SW England. This involved mapping and associated structural, sedimentological and biostratigraphic work in the areas between Dartmoor and Bodmin Moor and farther west on the north Cornish coast. This work has gone a long way towards unravelling the complex stratigraphical and structural relationships in central SW England: in particular the recognition of major nappe structures has helped to explain the existence of large areas of flat-lying, often inverted, Upper Devonian and Carboniferous strata (Stewart 1981; Isaac *et al.* 1982; Selwood *et al.* 1985; Selwood & Thomas 1984, 1985, 1986a, 1986b; Whiteley 1984; Isaac 1985; Turner 1985). These authors, hereafter referred to as the 'Exeter group', also recognize the

importance of northwards prograding flysch sedimentation. Another important implication is the rejection of the existence of the zone of south-facing first phase folds, the facing confrontation and the idea of southwards transport for the nappes (Isaac *et al.* 1982; Selwood & Thomas 1984, 1985, 1986a; Selwood *et al.* 1985). It is argued that all the first phase folds face northwards and that the nappes of Upper Devonian and Carboniferous rocks (of central SW England) are derived from the south by gravity sliding (Stewart 1981; Isaac *et al.* 1982; Selwood & Thomas 1984, 1985, 1986b, 1988; Selwood *et al.* 1985; Isaac 1985; Turner 1985).

In this paper we describe the geology of a transect from the SW Devon coast, northwards through Plymouth and up the Tamar Valley (Fig. 2). This transect crosses the postulated confrontation as projected ESE from the north Cornish coast (Sanderson & Dearman 1973; Hobson & Sanderson 1983). Inland exposure in SW Devon is extremely poor and work has been confined mainly to coastal reaches. However, in Plymouth road and railway cuttings, quarries and the banks along the River Tamar provide ample exposure. Part of the work has involved re-mapping and detailed investigations of sheet dip, fold vergence, facing directions and sedimentary younging within the rocks of the Plymouth Group (see stratigraphy section). This has revealed a more complex tectonic history than that previously described. Lithological observations on the original 6" maps (Ussher 1907) have proved to be invaluable.

Stratigraphy

The Palaeozoic rocks of SW Devon (Fig. 3) range in age from Lower Devonian (Siegenian) to Carboniferous (Viséan) and generally young from south to north. To the south of Plymouth the rocks are of Lower to Middle Devonian age, whilst in the city of

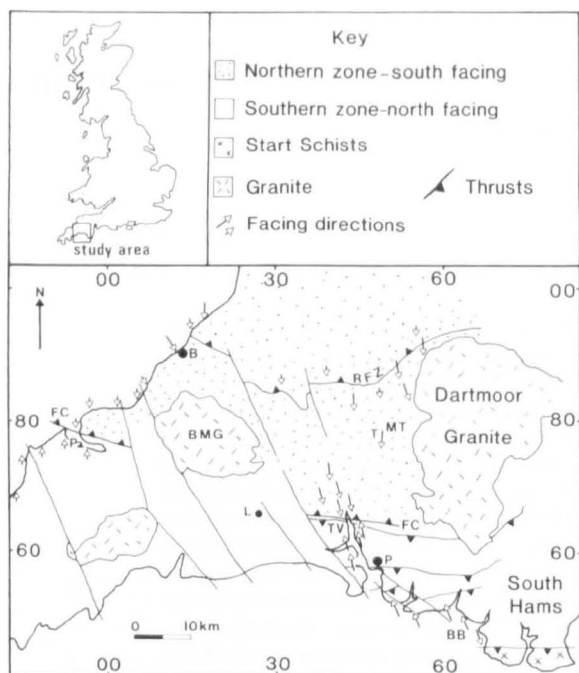


Fig. 1. Location maps showing the distribution of fold facing directions in central SW England. Arrows with long tails are observations made by the authors. Short-tailed arrows are observations made by others (referred to in the text). B, Bosccastle; BB, Bigbury Bay; BMG, Bodmin Moor Granite; FC, Facing Confrontation; L, Liskeard; MT, Mary Tavy; P, Plymouth; Pa, Padstow; RFZ, Rusey Fault Zone; T, Tavistock; TV, Tamar Valley.

Plymouth they range from Middle to Upper Devonian. Carboniferous rocks are found farther north in the St Mellion area (Fig. 2).

Lower Devonian

The oldest rocks are the Dartmouth Slates (Ussher 1907), re-named the Dartmouth Beds and which yield Siegenian fossils (Dineley 1966). Hendriks (1951) indicated that the Dartmouth Slates could be sub-divided into lithological units but she made no attempt at erecting a formal stratigraphy. Dineley (1966) showed that the Dartmouth Beds were divisible into four mappable units and so erected a lithostratigraphy. His four units are; the Wembury Siltstones (youngest), the Yealm Formation, the Scobbiscombe Sandstones and the Warren Sandstones (oldest). This was later proved to be upside down (Hobson 1976a), however, Dineley's lithostratigraphical units are still essentially correct, although some revision is necessary. We show that the Wembury Siltstones are divisible into two units, the Renney Rocks Formation and the Wembury Formation. Secondly the term Scobbiscombe Sandstones is omitted from our lithostratigraphic sequence for reasons explained below. This leaves four formations: the Renney Rocks Formation (oldest), the Wembury Formation, the Yealm Formation (cf. Dineley 1966) and the Warren Formation (youngest). We suggest that these should be included in the Dartmouth Group extending south-westwards along the coast from Andurn Point [SX 4900 4980] to Wadham Rocks [SX 5800 4680]. Faulting has repeated this succession between Wadham Rocks and Westcombe Beach [SX 6350 4575] (Fig. 4).

Renney Rocks Formation. This formation extends along the coast from Andurn Point in the north to Heybrook Bay [SX 4970 4875] in the south, and contains the oldest rocks seen in SW Devon. The dominant lithology is red or pink sandstone with

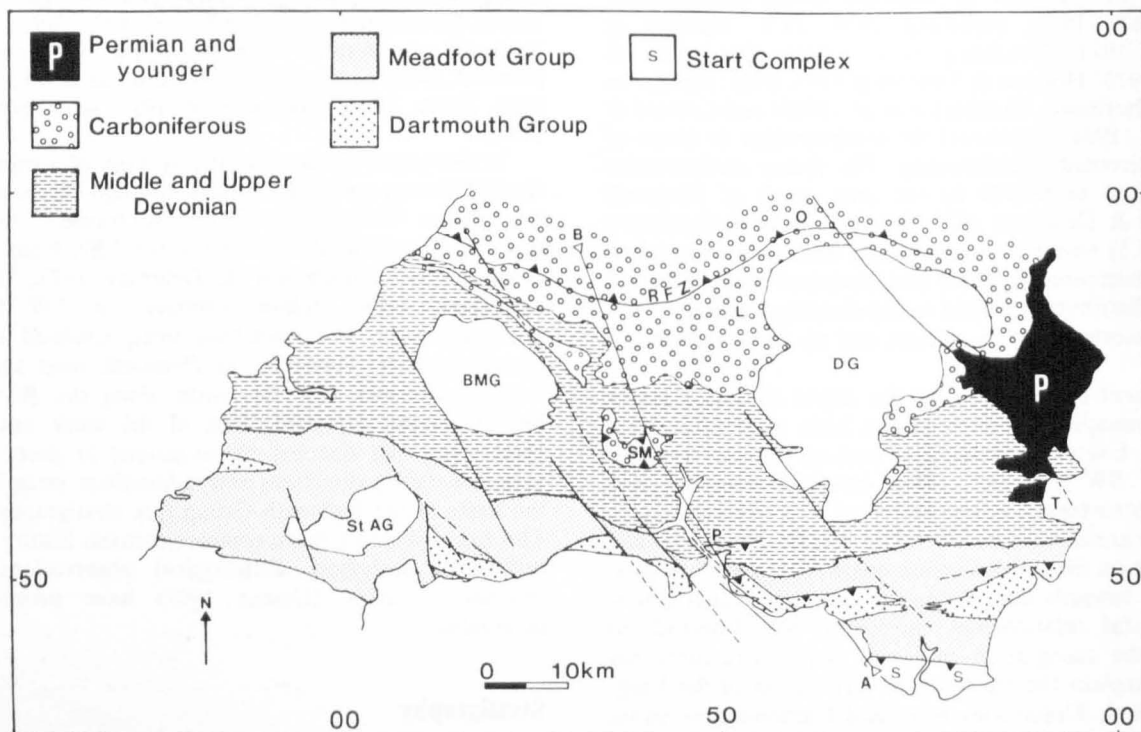


Fig. 2. Simplified regional geology of central SW England. A-B is the transect from which observations are used to construct the sections shown in Figs 6, 7 & 15. BMG, Bodmin Moor Granite; DG, Dartmoor Granite; L, Lydford Gorge; P, Plymouth; RFZ, Rusey Fault Zone; StAG, St Austell Granite; SM, St Mellion; T, Torbay.

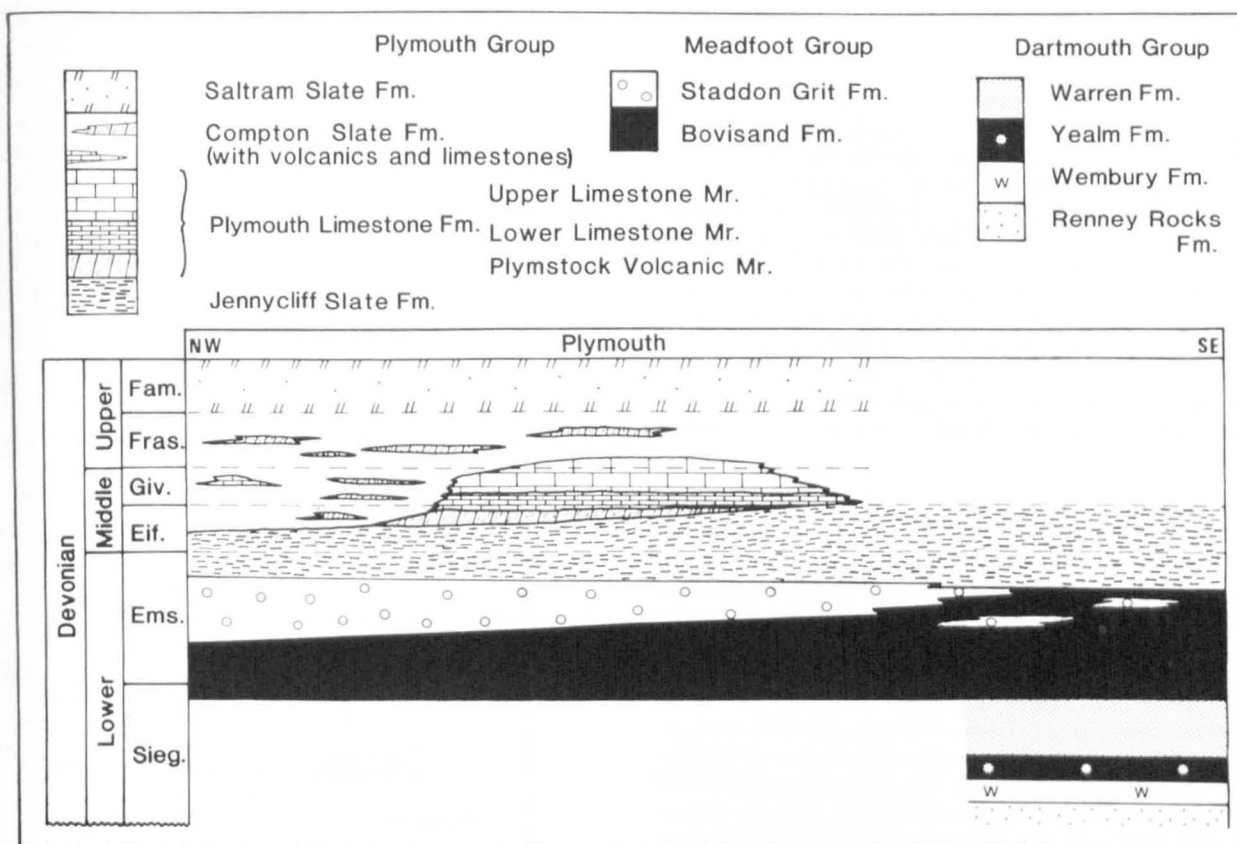


Fig. 3. Schematic representation of the Devonian stratigraphy along a NW-SE section through Plymouth (not to scale). Base of the Dartmouth Group not seen. Sieg., Siegenian; Ems., Emsian; Eif., Eifelian; Giv., Givetian; Fras., Frasnian; Fam., Famennian.

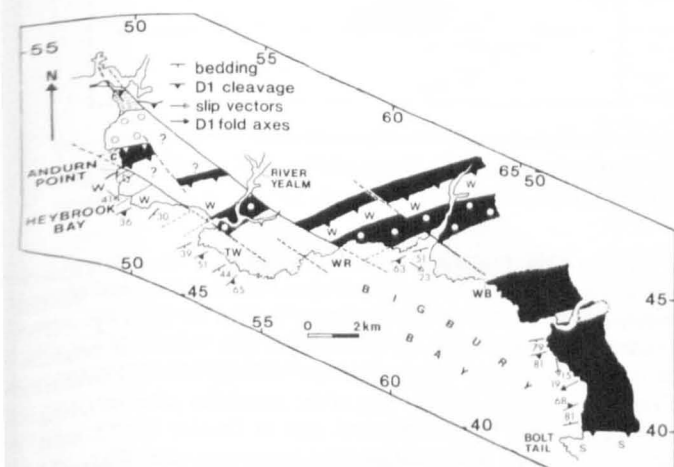


Fig. 4. Geological map of the western coast of the South Hams region. Ornament to stratigraphy as in Fig. 3. C, Crownhill Bay; TW, The Warren; WB, Westcombe Beach; WR, Wadham Rocks.

green and red slate and matrix-supported conglomerates. The formation's northern boundary is cut out by a fault and its base is not seen.

Wembury Formation. The Wembury Formation encompasses Wembury Bay and extends from Heybrook Bay in the west to the mouth of the Yealm estuary [SX 5275 4810] in the east. It is dominated by red and green slate but occasional sandstone beds, which may be 1 m thick, and volcanoclastics are present. From the

cross-sections it is determined that the stratigraphic thickness of this formation is c. 600 m.

Yealm Formation. Along with sandstone and slate this formation also contains volcanics. It occurs in the vicinity of the Yealm estuary, the river Yealm having eroded along the outcrop of the easily weathered volcanics (tuffs and volcanoclastics). Dineley (1966) estimated that the ratio of volcanics to slate and sandstone was 20:80. The presence of volcanics cause this formation to weather to many colours allowing it to be easily distinguished in the field. Many of the sandstone beds weather a yellow colour due to the presence of volcanic material. Black slates are present in this formation and do not occur anywhere else in the Dartmouth Group. The thickness of the formation is of the order of 300 m.

Warren Formation. This formation occurs to the south of the Yealm estuary from [SX 5300 4750] in the west along the coast of the Warren to Wadham Rocks [SX 5800 4680] in the east. Lithologically it is very similar to the Wembury Formation but contains a higher proportion of sandstones. A sequence of these sandstones has been mapped as a separate unit by Dineley (1966), at Beacon Point [SX 6155 4600], and was called the Scobbiscombe Sandstones. Due to the fact that the Warren Formation contains many sequences of sandstones, although none as thick as the Scobbiscombe Sandstones, it is not considered necessary to include them as separate lithostratigraphic units. The Warren Formation is c. 3000 m thick.

The rocks of the Meadfoot Group conformably overlie those of the Dartmouth Group. In this paper we have divided the Meadfoot Group into the Bovisand Formation (Bovisand Beds of Harwood 1976) and the Staddon Grit Formation (Chandler & McCall 1985).

The Meadfoot Group has been dated on the basis of brachiopods as being Emsian in age (Evans 1981, 1983, 1985) and essentially shows a coarsening upwards succession. The Bovisand Formation, which is mainly argillaceous and marine in origin, is overlain by the Staddon Grit Formation which is coarser and may represent a southward prograding deltaic sequence (Pound 1983). Due to the complex facies relationships within the Meadfoot Group it is often difficult to determine one formation from the other, especially in areas of poor exposure. The above descriptions apply to the rocks on the east side of Plymouth Sound between Jennycliff Bay [SX 4915 5185] in the north, and Andurn Point in the south. The rocks of the Meadfoot Group also occur towards the southern end of the area, at Bigbury Bay (Fig. 4). Here the lithologies are predominantly black slates and are therefore attributed to the lower part of the Meadfoot Group. However, coarser deposits are present (Beeson Grits of Ussher 1907) which are probably lateral equivalents of the Staddon Grit Formation.

Middle and Upper Devonian

The Lower/Middle (Emsian/Eifelian) Devonian boundary occurs in the Jennycliff Slate Formation (cf. Chandler & McCall 1985) which conformably overlies the Staddon Grit Formation (Ussher 1907; Hobson 1976a; Chandler & McCall 1985). Farther north in the Plymouth city area, there is a succession of limestones, volcanics and slates which are Middle Devonian (Eifelian) to Upper Devonian (Famennian) in age (Ussher 1907; Gooday 1975; Orchard 1978). By combining the biostratigraphic information of Gooday (1975) and Orchard (1978) with our own lithostratigraphical and structural observations, and by comparing this with the Upper Devonian stratigraphy of the Liskeard area (Burton & Tanner 1986), we have been able to elucidate the stratigraphy and the structure in the Plymouth and Tamar region. It is proposed that the Middle/Upper Devonian succession around Plymouth should be referred to as the Plymouth Group extending north-westwards from Jennycliff Bay [SX 4915 5185] to Warleigh House [SX 4560 6170], at the mouth of the River Tavy (Figs 3 & 5). The younger rocks to the north belong to the Cann Wood Formation (cf. Chandler & McCall 1985). The Plymouth Group is divided into five lithological formations, some of which are retained from previous work (cf. Chandler & McCall 1985). These authors refer to the Jennycliff slates as the Jennycliff Slate Formation. Above this they divide the Plymouth Limestone Formation into three members, the Plymstock Volcanic Member, the Lower Limestone Member and the Upper Limestone Member. We agree that there is a lower unit of calcareous slate and an upper unit of massive limestone. Previously this Formation had been known simply as the Plymouth Limestone (Ussher 1907; Hobson 1976a). The Plymouth Limestone Formation is only locally developed and it passes northwards, laterally and upwards into a sequence of slates which are Eifelian–Famennian in age (Saltash unit of Turner 1986; Plympton Slate Formation of Chandler & McCall 1985). Within the Plympton Slate Formation there are two distinct mappable units to which it is felt necessary to assign Formation status (see Fig. 5 for the distribution of these formations). It is proposed that the Plympton Slate Formation should be replaced by the Compton Slate Formation (oldest) and the Saltram Slate Formation.

Compton Slate Formation. The lower of the two units mentioned is referred to as the Compton Slate Formation (Eifelian–Frasnian) and is composed of grey and black slate. Limestones are locally developed and volcanics (tuffs and vesicular pillow lavas) occur as sheets and not as one member as indicated by Chandler & McCall (1985). This formation is exposed to the north and south of the Plymouth by-pass [SX 4900 5730] as well as in roadside cuttings. Volcanics are common to the south of the by-pass in the Compton area of Plymouth [SX 4950 5650] (Fig. 5).

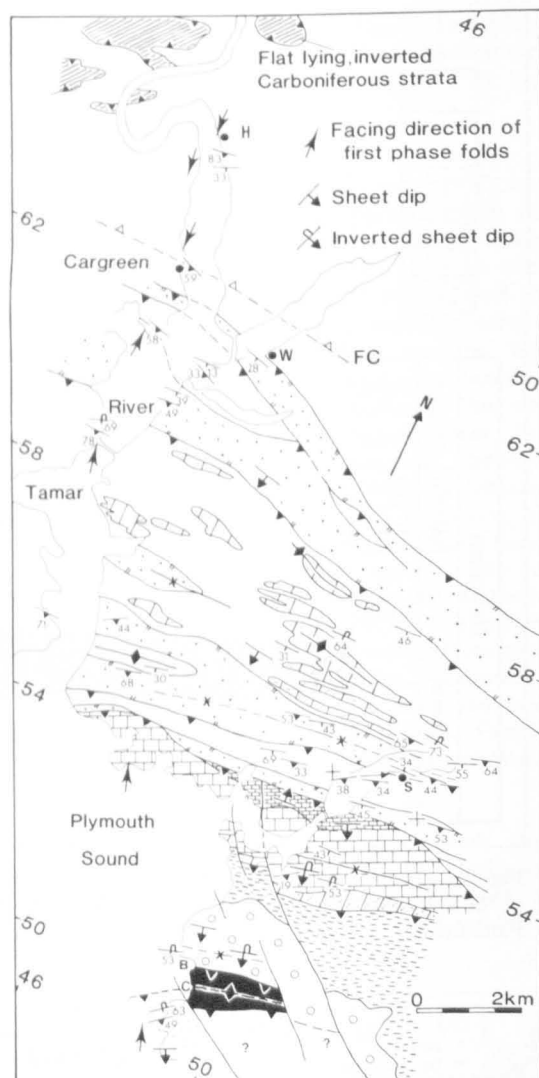


Fig. 5. Geological map of the Plymouth area. Ornament to stratigraphy as in Fig. 3. B, Bovisand Bay; C, Crownhill Bay; H, Hole's Hole; W, Warleigh House.

Saltram Slate Formation. Above the Compton Slate Formation is a sequence of purple and green slates which form two distinct mappable belts (Fig. 5) (cf. Chandler & McCall 1985, p. 255). Volcanics and limestones are absent from this formation which is referred to, in this paper, as the Saltram Slate Formation (Famennian in age). For this part of the succession palaeontological evidence is scarce but the ostracod ages of Gooday (1975) can be used to compare the stratigraphic sequence with that dated accurately by Burton & Tanner (1986), along strike in the Liskeard area. The type section is located along the east shore of the River Plym, to the west of Saltram House [SX 5195 5565].

North of Plymouth the rocks overlying the Saltram Slate Formation are grey slates with occasional sandstone bodies (not shown in Fig. 3). These probably represent shallowing after long-lived deeper marine conditions which gave rise to the deposition of the Upper Devonian Slate Formations farther south. It appears that they are equivalent to the Kate Brook unit (Waters 1970; Isaac *et al.* 1982; Turner 1986) or the Cann Wood Formation (Chandler & McCall 1985).

Structurally and stratigraphically overlying these Upper Devonian rocks are Lower Carboniferous deposits of the St Mellion outliers (Ussher 1907) which are Tournasian and Viséan in age

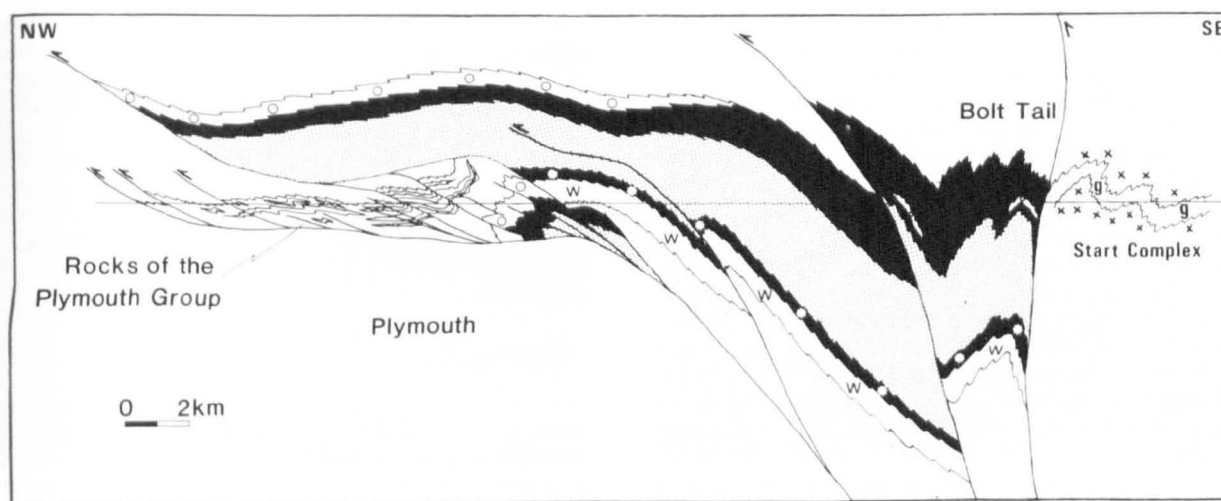


Fig. 6. Balanced section through the north-facing southern zone. Ornament to stratigraphy as in Fig. 3. Line of section shown in Fig. 2. Start Complex: g, greenschist; x, greyschist.

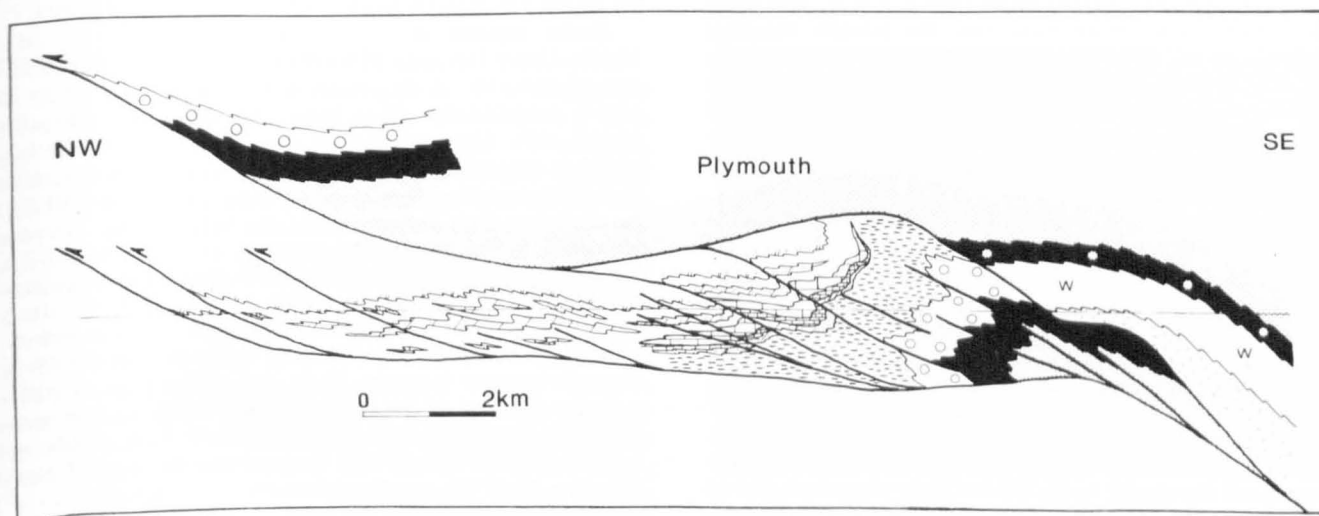


Fig. 7. Balanced section through the city of Plymouth (enlarged portion of Fig. 6). Indicates 37.5% bulk shortening when compared with the restored section (Fig. 8). Ornament to stratigraphy as in Fig. 3. Section line shown in Fig. 2.

Heathfield Nappe of Isaac *et al.* 1982; Whiteley 1984; Blackdown Nappe of Turner 1986; Boscastle Nappe of Selwood & Thomas 1988). The stratigraphic relationships in this area are complicated by overturned nappes and thrusts.

Structures of the southern zone

The southern zone covers the area between the Start peninsula and Cargreen, 8 km north of Plymouth (Fig. 1). It is dominated by structures which verge and face northwards, representing the northward migration of the Variscan deformation front across SW England (Matthews 1977; Shackleton *et al.* 1982; Hobson & Sanderson 1983). A detailed study has been undertaken in the Plymouth City area and to the south along the south Hams coastline, the results of which are shown as cross-sections in Figs 6 & 7. The sections have been balanced and the effects of minor folds and cleavage formation have been taken into account. Figure 7 has been restored (see Fig. 8) and shows that 37.5% bulk shortening has occurred during deformation. Figure 6 has also been partially restored (not figured) and indicates a bulk shortening of 61%.

Balancing and restoring of the sections are complicated due to the presence of a series of strike-slip faults parallel to them (see Fig. 2). These faults divide the region into compartments and structures cannot always be matched across them. It is not possible to limit the structural observations to one compartment for the whole section.

South Hams coastal region

This belt of Lower Devonian rocks, to the south of Plymouth, is dominated by structural features which indicate transport to the north-west. Thrusts dip to the south-east and slip vectors on these surfaces also plunge to the south-east. D1 fold axes have a SW-NE trend and belong to a suite of folds which are asymmetric and overturned towards the north-west. These features indicate NW-directed simple shear deformation typical of this part of the Variscan orogen (Hendricks 1951; Sanderson & Dearman 1973; Hobson 1976b; Matthews 1977; Shackleton *et al.* 1982; Hobson & Sanderson 1983; Coward & McClay 1983; Coward & Smallwood 1984). Associated with the D1 folds is a penetrative, axial planar slaty cleavage in the mudrocks which indicates that the primary folds are upward-facing towards the NW.

Early workers recognized the northward overturning of the D1 folds, and in some cases the northward transport by thrusting (Ussher 1907; Hendricks 1951; Fyson 1962; Hobson 1976a, 1976b). However, the implications of thrust tectonics were not considered on a regional scale. In the last few years, major thrusts have been recognized in the Plymouth area and to the south along the coast towards Bolt Tail [SX 6700 3900] (Chapman 1983; Chapman *et al.* 1984). Thrusts have also been recognized along a similar line of section to the south of Torquay (Ussher 1903; Vachell 1963; Coward & McClay 1983). The thrusts and early folds are therefore the main structural agents producing the present outcrop pattern in south Devon. Chapman *et al.* (1984) suggested that the Plymouth Limestone Formation was thrust northwards over the Upper Devonian slates. This relationship was also recognized by Chandler & McCall (1985) who also show, on their schematic section through Plymouth, a thrust at the southern margin of the Plymouth Limestone Formation.

The following descriptions apply to the coastline south of Plymouth as far as Bolt Tail (see Figs 4 & 6). The oldest Devonian rocks of this area are those of the Dartmouth Group. They lie within a NE–SW-trending structure known as the Dartmouth Antiform (Hobson 1976b) which we interpret as having formed above a major SW–NE-trending thrust (Figs 2, 4 & 5). This thrust emplaces Dartmouth Group rocks over the younger Meadfoot Group rocks in the vicinity of Crownhill Bay [SX 4925 4980] (see Fig. 5). The thrust is not exposed here due to displacement by a NW–SE-trending strike-slip fault (previously described as a vertical fault with 3700 m displacement by Hobson 1976a). D1, north-west-verging parasitic folds occur on the Dartmouth Antiform some of which are associated with thrusts.

The Meadfoot Group rocks, which underlie the thrust at Crownhill Bay, are sub-divided into the Bovisand Formation and the younger Staddon Grit Formation. The boundary between these two formations can be traced through Bovisand Bay [SX 4920 5060] and is interpreted as a southerly dipping thrust (Fig. 5). This interpretation is supported by the geometry of the D1 folds in both the hanging-wall and footwall. The Bovisand Formation, above the thrust, occupies a north-verging anticlinal structure (hanging-wall anticline) with small scale parasitic folds disrupted by minor thrusts. The rocks of the Staddon Grit Formation, below the thrust, are overturned and dip steeply to the SE and their vergence is also in this direction. Farther north they become the right way up and flat lying, giving them an overall synclinal structure (footwall syncline to the Bovisand Thrust). Other supporting evidence is the presence of localized but well developed zones of folded cleavage in the hanging-wall. These folds plunge gently WSW or ENE (co-axial to the early folds) and have an associated, steeply dipping crenulation cleavage. The association of thrusts and the development of folded cleavage is commonly observed throughout the area. Minor thrusts have previously been described within the Staddon Grit Formation and the overlying Jennycliff Slate Formation (Chapman 1983; Chapman *et al.* 1984).

The southerly sheet dip section (Fig. 6) increases to the south-east, and this led Hobson (1976b) into believing that the Dartmouth Antiform was a modified D1 fold. Coward & McClay

(1983) explained the geometry in terms of a deep level backthrust producing backsteepening at the southern end of the section. The backsteepening effect is responsible for the present steep attitude of cleavage, faults (e.g. Start Fault) and bedding, and is reflected by the presence of a northward dipping crenulation cleavage and northward dipping thrusts. The relationship of deformation phases across the Start Fault is currently under review as part of a PhD thesis (R. D. Seago) and it seems that there is an early phase in the Start Schists which is not seen in the Devonian sequence to the north (Marshall 1962, 1965; Hobson 1977; see also Coward & McClay 1983).

The Plymouth City region

The structure of the Middle and Upper Devonian succession, which includes slate, limestone and volcanics of the Plymouth Group, has not been satisfactorily deciphered in the Plymouth area. Accurate structural cross-sections have previously been constructed only in the Liskeard area, 20 miles north-west of Plymouth (Tanner 1985; Burton & Tanner 1986). Recent work in the Plymouth area has been carried out by Chandler & McCall (1985) but they only present a schematic cross-section. They describe the stratigraphy but do not pay attention to the small-scale structural features.

Rocks exposed in the Plymouth City area are of the Middle–Upper Devonian Plymouth Group (Fig. 5). The distribution of this part of the Devonian succession varies little from already published data (BGS Sheet nos 348 and 349; Chandler & McCall 1985). However, there is one striking difference which is crucial to unravelling the structure of the area. This is the division of the Plympton Slate Formation of Chandler & McCall (1985) into the Compton Slate Formation and the Saltram Slate Formation (described in the stratigraphy section). Along the River Tamar section, the Compton and Saltram Slate Formations are repeated by a series of folds and thrusts which indicate northerly directed transport. The present erosion level is just above or just below the boundary between the Compton Slate Formation and the Saltram Slate Formation. It seems likely that a flat-lying décollement underlies this part of the section. Thrusts which cut the present erosion level probably curve into this plane at depth. Folds which occur in the higher levels may be developed above blind thrusts. The sheet dip of this area is sub-horizontal (Figs 5, 6 & 7).

Minor folds are observed in many of the slate quarries: they are asymmetric, face north, and generally have a northwards vergence. Some minor folds and cleavage vergence may be to the north or south depending upon which limb of the larger folds they are observed. These minor folds are common in the slate formations but they are rare in the more competent limestones. The Plymouth Limestone Formation is folded into a major syncline and is bounded to the north and south by thrusts (Fig. 7). The isolated outcrops of volcanics (tuffs and vesicular pillow lavas), which occur within the Compton Slate Formation (grey and black slate), are shown on the BGS maps (Sheet nos 348 and 349) and in Fig. 5. Bedding/cleavage relationships demonstrate that their outcrop pattern is due to the folding of volcanic sheets, with the present volcanic outcrops occurring within anticlinal culminations.

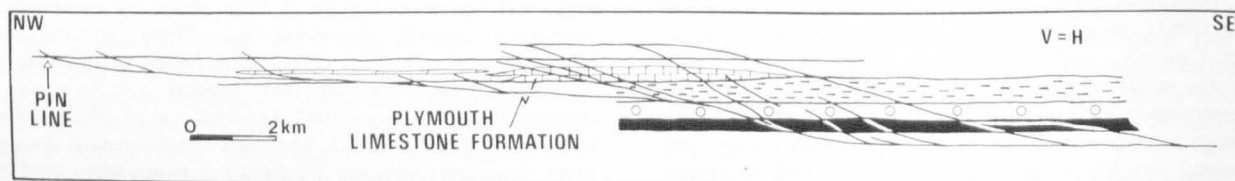


Fig. 8. Restored section through the city of Plymouth (Compare with Fig. 7).

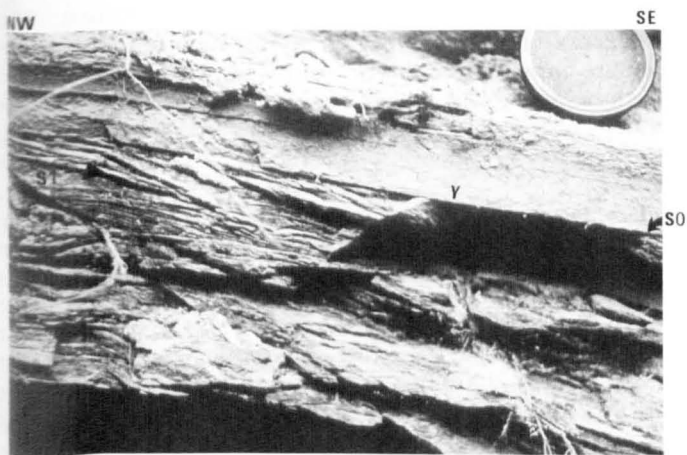


Fig. 9. Example of cleavage/bedding relationships in Carboniferous rocks at [SX 4160 6500] (see Fig. 12), on the east shore of the River Tamar. The beds are inverted and south-east-facing on the cleavage is indicated.

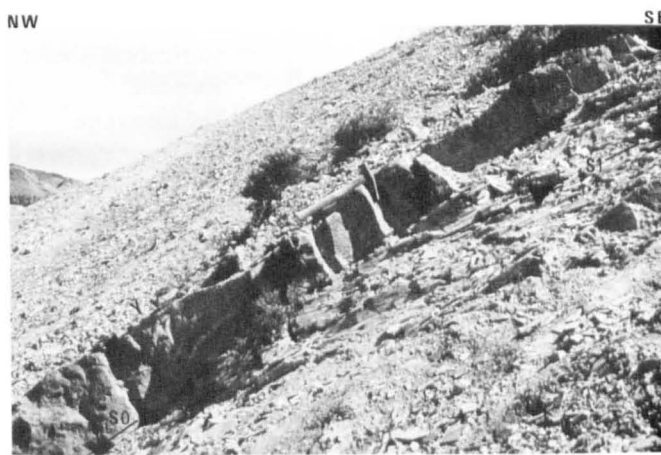


Fig. 10. Cleavage/bedding relationships in the Wheal Betsy stream section [SW 5090 8070] near Mary Tavy (see Fig. 1). Beds are inverted and this gives south-east facing on the cleavage.

Structures of the northern zone

This zone extends northwards from Cargreen [SX 4350 6275] into central Devon between the Dartmoor and Bodmin Moor granites (Figs 1 & 5), where Upper Devonian and Lower Carboniferous strata are exposed (see Fig. 2). Structurally the area is dominated by facing towards the south or south-east and although D1 folds occur the facing is more commonly observed on the D1 cleavage. Southward facing has been observed in the St Mellion, Tavistock, Mary Tavy and Lydford Gorge areas (see Figs 1 & 2).

The 'outlier' of Carboniferous strata exposed in the St Mellion area [SX 3880 6600] (Fig. 2) is inverted. Beds are graded and contain flame structures (Isaac *et al.* 1983; Whiteley 1984). A southerly dipping D1 penetrative cleavage crosses the generally horizontal bedding. This indicates that the facing on the cleavage is to the south (Cleave Quarry, SX 4034 6851; River Tamar, SX 4160 6500; Fig. 9). Similar relationships are seen at Cothele Quarry [SX 4180 6801]. From this it can be inferred that the Carboniferous outlier represents the lower overturned limb of a southwards closing fold nappe, indicating transport towards the south.

The rocks of the Crackington Formation (Isaac *et al.* 1983) exposed at Wheal Betsy, near Mary Tavy, contain a D1 cleavage which dips NW at a shallower angle than bedding. The sandstones possess bottom structures in the form of flute casts indicating that the beds are overturned. This bedding/cleavage association along with the direction of younging gives south-east facing on the cleavage (Fig. 10).

The Upper Devonian strata exposed along the shores of the River Tamar at Hole's Hole [SX 4320 6520] contain flame structures and graded beds which indicate overturning. Northward verging D1 folds are present with horizontal long limbs and vertical short limbs. The primary axial planar cleavage dips to the south. This geometry shows that the folds are downward-facing towards the south (Fig. 11). Just north of Cargreen the flat-lying primary cleavage is deformed into north-verging folds which possess an axial planar, south-dipping crenulation cleavage.

We have also visited the Lydford Gorge area where Sanderson & Dearman (1973) recognized southward-facing structures. This interpretation is supported on the basis of younging (overturned beds), bedding (horizontal) and cleavage (south dipping) in the Upper Devonian strata. The same relationships occur in the rocks exposed in the stream section at Tavistock [SX 4825 7455].



Fig. 11. North-verging fold at Hole's Hole [SX 4320 6520] (see Figs 5 & 12). Sheet dip is horizontal and beds are inverted with south-dipping cleavage. This indicates south facing.

The facing confrontation

A facing confrontation of first phase folds was initially described on the north Cornwall coast near Padstow [SW 9200 7500] (Gauss 1967, 1973; Dearman 1970, 1971; Roberts & Sanderson 1971; Sanderson & Dearman 1973; Hobson & Sanderson 1975, 1983; Sanderson 1979; Shackleton *et al.* 1982) where a belt of north-facing, first phase structures is developed to the south and a zone of south-facing, first phase structures to the north. With the confrontation defined at the coast, subsequent investigations took place in central Devon where south or south-east-facing was discovered in the Mary Tavy, Lydford and Okehampton areas (Sanderson & Dearman 1973). These structures oppose the northward directed early folds of SW Devon and Cornwall and so the above authors inferred a confrontation similar to that seen farther west. However, it was not pinpointed precisely in the area north of Plymouth.

During the present research programme the confrontation of north- and south-facing first phase folds has been accurately located as passing through Cargreen [4350 6275].

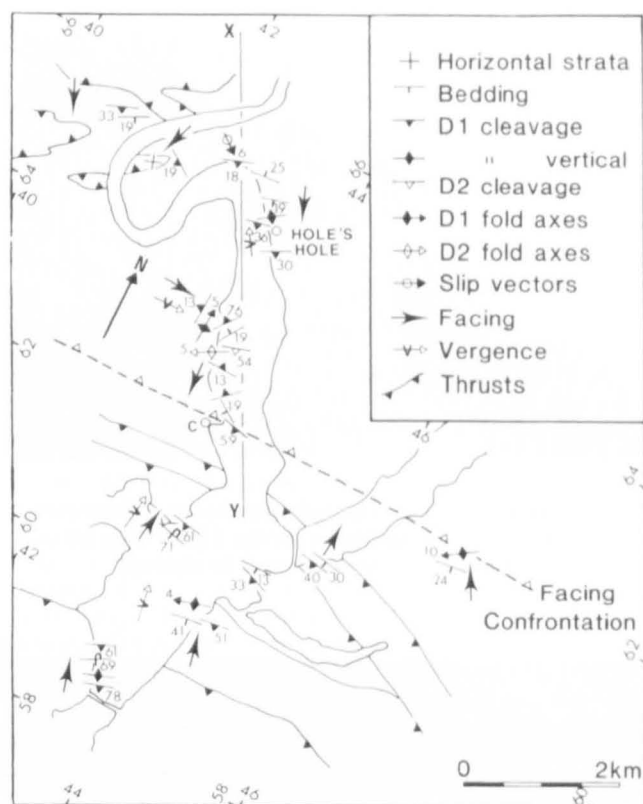


Fig. 12. Structural map of the Cargreen (C) area. For section X-Y see Fig. 13.

8 km north of Plymouth in the Tamar Valley (Fig. 12). Folds immediately to the south of Cargreen are northward and upward-facing with respect to the D1 slaty cleavage and their vergence is to the north. Thrusts which disrupt this essentially upright Famennian sequence also have a movement direction to the north or north-west. To the north of Cargreen the strata are predominantly overturned and facing on the cleavage is to the south or south-east. Thus at Cargreen there is an E-W-trending facing confrontation which we interpret as a northerly dipping thrust. Similarly, Gauss (1973) interpreted the facing confrontation at Padstow as a northerly dipping thrust.

There is a remarkable contrast between the two zones. The products of the northward-transporting Variscan deformation are upright to northerly overturned, north-verging and north-facing folds. Although large scale thrust nappes are a product of this deformation episode there is no overturning of strata on a regional scale. This is in contrast to the northern zone, to the north of the facing confrontation, where thrust-related fold nappes give rise to large-scale overturning of strata. Work by the Exeter group covers the area north of Plymouth. They postulate that the fold nappes were transported towards the north by gravity sliding (Isaac *et al.* 1982; Selwood & Thomas 1985, 1986a) and suggest that southward movement is not encountered until the Rusey Fault zone is crossed (see Fig. 1). The present authors believe that the early folds between the Rusey Fault Zone and Cargreen indicate nappe transport towards the south. The early folds in this zone are then overprinted by northerly directed structures which are D2 in age.

The cleavages which form as products of the D2 deformation have different forms north and south of the confrontation. The slaty cleavage in the northern zone is flat-lying and the facing is towards the south whilst the D1 cleavage in the southern zone dips at 30–40° to the south or south-east and the facing is towards the north or north-west (Figs 12 & 13). These cleavages probably formed at different times as a result of progressive deformation from south to north and represent the earliest deformation in their respective areas. At the confrontation there is a zone of intense deformation. The flat-lying D1 cleavage is deformed into northward verging folds which possess an axial planar crenulation cleavage, dipping at 40–50° to the south. These features are referred to as the D2 structures. Roberts & Sanderson (1971) argued a similar history for the development of cleavages on the north Cornish coast. Also, Burton & Tanner (1986) describe a D2 zone in the Liskeard area. The position of this D2 zone, if projected eastwards, along strike, would lie approximately in a similar position to the D2 deformation zone described by the present authors.

The existence of south-facing folds at the southern margin of the Culm Measures is well documented (Sanderson & Dearman 1973; Hobson & Sanderson 1983). Fold axial planes are vertical at Bude, but farther to the south they usually dip to the north (Crackington Haven) and in some cases are horizontal (Millook Haven) (Sanderson 1979). At these localities, and as far south as the Rusey

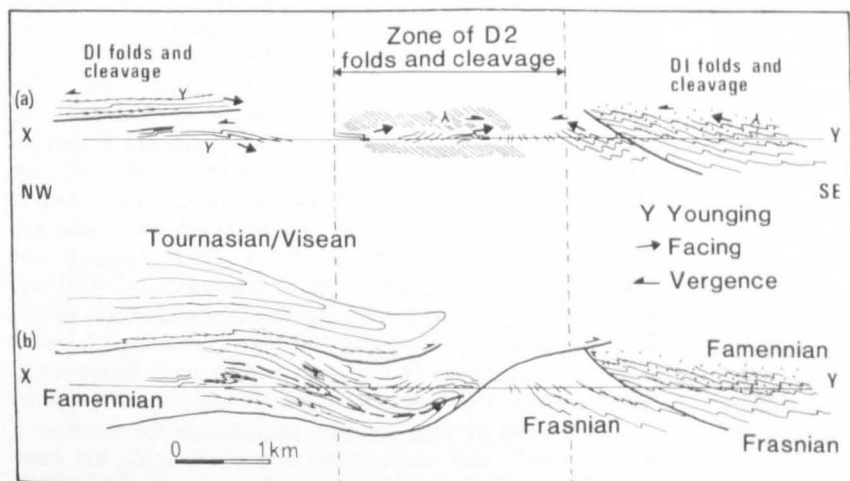


Fig. 13. (a) Structural relationships along a NW-SE transect through the facing confrontation. Line X-Y in Fig. 12. (b) Interpretation of the facing confrontation.

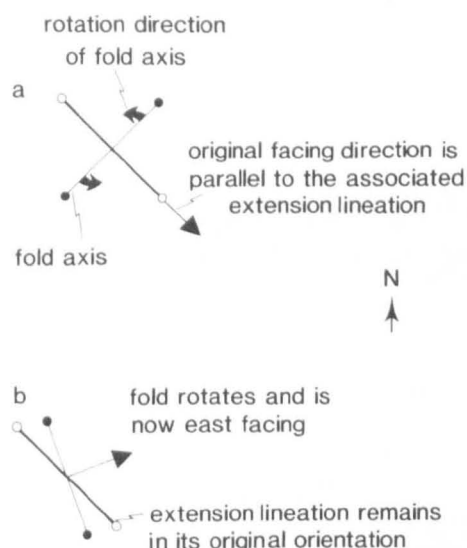


Fig. 14. Diagram showing how east-facing recumbent folds at Boscastle have rotated toward the maximum extension direction from an original south-east-facing direction (further explanation in the text).

Fault Zone (RFZ), it can be demonstrated that facing is undoubtedly in a southwards direction (Fig. 1). It is the area to the south of the RFZ that has caused a difference of opinion in recent years. Several workers have described the area between Rusey and Polzeath as facing south with respect to D1 folds (Roberts & Sanderson 1971; Gauss 1973; Sanderson & Dearman 1973; Hobson & Sanderson 1975; Shackleton *et al.* 1982). Recently the Exeter group has been working in this area and in the equivalent area along strike north of Plymouth, the area which is equivalent to the northern zone described in this paper. In contrast to the earlier work they have described the whole zone in terms of northward transport of the first phase structures (Isaac *et al.* 1982; Selwood & Thomas 1985, 1986a). There is no controversy over the fact that the D2 deformation episode has a northerly sense of movement, as reported by them.

We have examined D1 recumbent structures at Boscastle, with NNW-SSE-trending fold axes, which face towards the E. The associated extension lineation trends NW-SE and so these folds can only have been rotated from an originally south-east-facing direction towards parallelism with the associated lineation (Fig. 14). Many of these east-facing D1 folds can be seen on Penally Hill [SW 0950 9200], just north of Boscastle. A well known D1 fold described by Dearman & Freshney (1966, fig. 6b) at Boscastle Harbour is upward facing. It lies within the steep limb of a flat-lying northward verging D2 fold. When the effect of the D2 fold is removed the original D1 fold becomes south-east facing, contrary to the comments of Selwood & Thomas (1986a). We argue that the zone of south facing does exist.

A foreland basin model

Any tectonic model for the evolution of central SW England has to account for the following features.

(1) A southern zone of north-westward-facing structures. This includes north-westward-verging folds, thrusts with a north-westerly sense of movement, and a penetrative

cleavage which dips to the south-east. This zone is composed of Devonian rocks.

(2) A northern zone of flat-lying, recumbent fold nappes which face south or south-east, with an associated flat-lying penetrative cleavage. This zone is composed of rocks of Upper Devonian and Lower Carboniferous age.

(3) A triangle zone and facing confrontation where the southern and northern zones meet.

(4) Within the northern zone, inverted strata, on the lower limbs of the recumbent fold nappes, generally lie above older rocks.

(5) A second phase of deformation intensely developed in the vicinity of the facing confrontation.

It is now well documented that deformation and sedimentation migrated northwards across SW England during latest Devonian/early Carboniferous times (Dearman 1971; Dodson & Rex 1971; Shackleton *et al.* 1982; Isaac *et al.* 1983; Sanderson 1984; Selwood & Thomas 1986b, 1988). The Tournasian and Viséan strata forming the fold nappes in the St Mellion area are immature, poorly sorted deposits containing plant debris indicating shallow water, deltaic sedimentation having a source to the south (Whiteley 1981, 1982, 1984). Isaac *et al.* (1983) and Turner (1986) have interpreted these Carboniferous rocks as flysch deposits and Selwood & Thomas (1986b, 1988) have suggested that they accumulated within a fore-deep in advance of a northerly migrating deformation front. Whilst we fully endorse this view we disagree with the suggestion that fold nappes then glided northwards under the influence of gravity (Isaac *et al.* 1982; Selwood & Thomas 1985, 1986a; Turner 1986). The small-scale structures demonstrate that the larger structures close to the south and face south or south-east. We have not observed any northward-facing first phase structures within the northern zone.

The foreland basin deposits (Beaumont 1981) were deformed 'soon' after deposition (Selwood & Thomas 1988) producing large southerly-facing fold nappes. (Figs 13b, 15 & 16). It is the overturned limbs of these nappes which are now mainly exposed in the northern zone. Clearly underthrusting of the foreland basin flysch deposits has occurred (Fig. 16). These structures no doubt developed during continental 'A' type subduction of the Variscan foreland beneath the fold thrust belt. Such a situation is documented in the Rocky Mountain foothills where a triangle zone has developed (Price 1981; Butler 1982; Jones 1982). In essence the migrating thrust front 'chisels' its way under the fore deep flysch deposits, which although remaining *in situ*, are thrust relatively backwards towards the hinterland.

We believe that the same phenomenon has happened in SW England and that during the underthrusting process the beds become overturned. A method of achieving this by employing the idea of a rolling hinge to the nappes (Shackleton 1979; Platt *et al.* 1983, Fig. 16a) in which material moves successively through the hinge onto the lower, overturned limb of the nappe (as shown by the reference points A, B, C & D in fig. 17). On the upper diagram in Fig. 17 point 'A' is above point 'X'. As material moves through the hinge point 'A' will eventually lie above point 'Y' (as seen in the lower diagram in Fig. 17). The lower limb is thus dragged downwards. This procedure allows the overturning of the nappe pile to occur at a slower rate than the underthrusting process and overturning of younger strata over older is achieved. Conventional

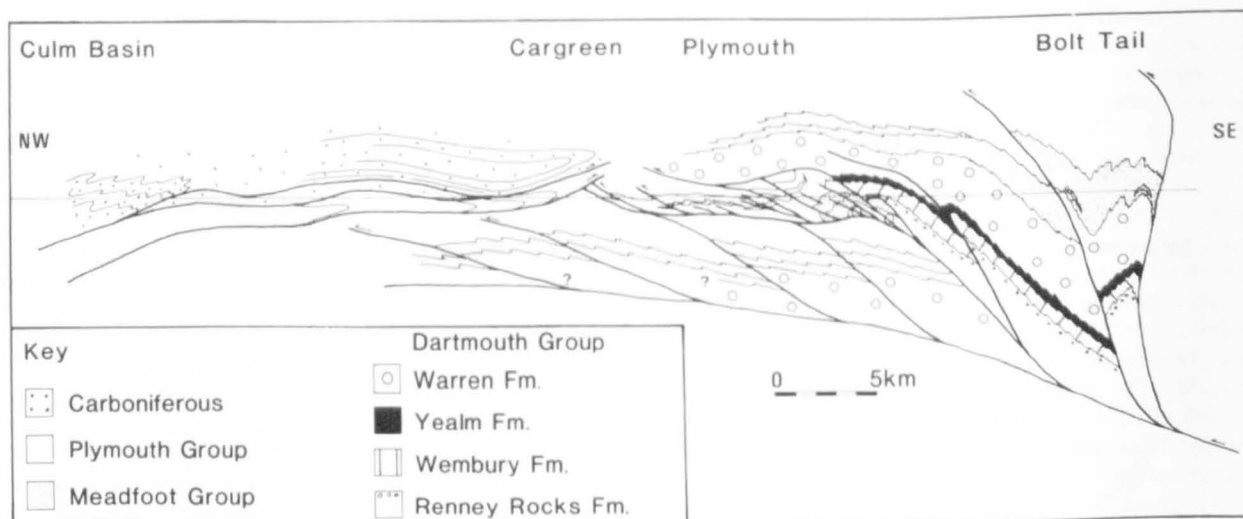


Fig. 15. Cross-section showing the possible deep structure and facing confrontation in SW Devon. Line of Section shown in Fig. 2.

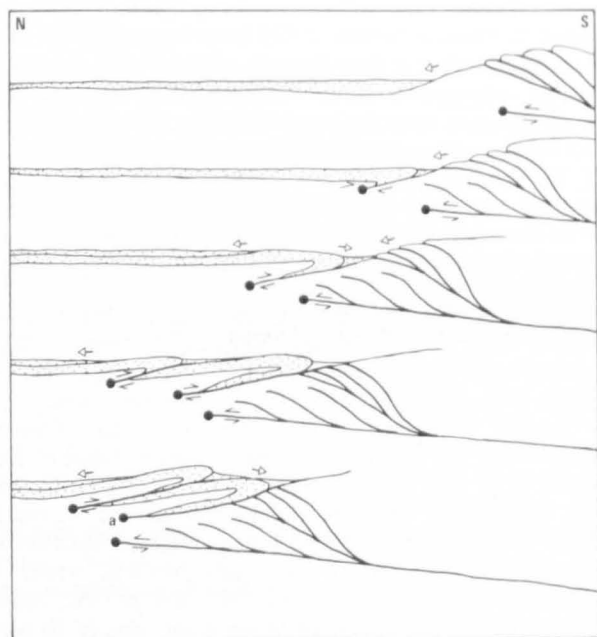


Fig. 16. Schematic evolutionary model showing the style of deformation at the southern margin of the Carboniferous basin in SW Devon, an inverted basin margin. In the lowest sketch the middle thrust (a) becomes inactive. Open arrows indicate sediment influx and half arrows indicate movement on an active thrust.

backthrust movement would emplace older strata on top of younger whilst the nappe pile moved southwards. The tips of the lower limb of the fold nappe and underthrusting proceed in a 'caterpillar track' fashion, in what we describe as underpeeling. Each nappe progressively accretes itself onto the front of the advancing thrust sheets (see Fig. 16). No material moves southwards towards the hinterland. It all moves northwards but the unconsolidated flysch deposits are relatively thrust in a southwards direction over the underthrusting, northwards moving foreland thrust belt.

Such a model also explains the intense development of second phase folds in the region of the confrontation. First phase structures were independently developed in the north and south, and when the underthrusting occurred those of the south overprinted those of the north in the region of the confrontation and produced a strong D2 crenulation fabric in the flysch deposits. The D2 structures have a northerly sense of movement due to the continuing northwards migration of the deformation front.

Deep structure

There are a number of possible sections which can represent the deep structure of SW England (Figs 15 & 18). They involve either a shallow (Fig. 18a) or deep (Fig. 18b), 'pop-up' structure (cf. Shackleton *et al.* 1982). The backsteepening at the southern end of the section may be due to a deep crustal backthrust (Coward & Smallwood 1984). However, backsteepening may also have been caused by normal foreland-propagating thrusts. We prefer a model in which the 'pop-up' is rather shallow and does not extend right down to the Variscan sole thrust (Fig. 18a). It may underlie only the foreland basin flysch deposits of the Culm Trough which experienced syn-sedimentary thrusting whilst still in an unconsolidated state during the Westphalian (Enfield *et al.* 1985; Whalley & Lloyd 1986). Both of these models are compatible with offshore deep seismic profiles (BIRPS & ECORS 1986).

Conclusions

In this paper we have shown that there are two distinct structural styles present in the Palaeozoic rocks of south Devon. Two zones occur: a southern zone with steeply to gently dipping sheet dips and northward-facing first phase structures; a northern zone with flat-lying and southward-facing primary structures. The two zones meet at a confrontation or triangle zone. We interpret the line of confrontation as a northerly dipping thrust, having a backthrust sense to the normal southward dipping Variscan

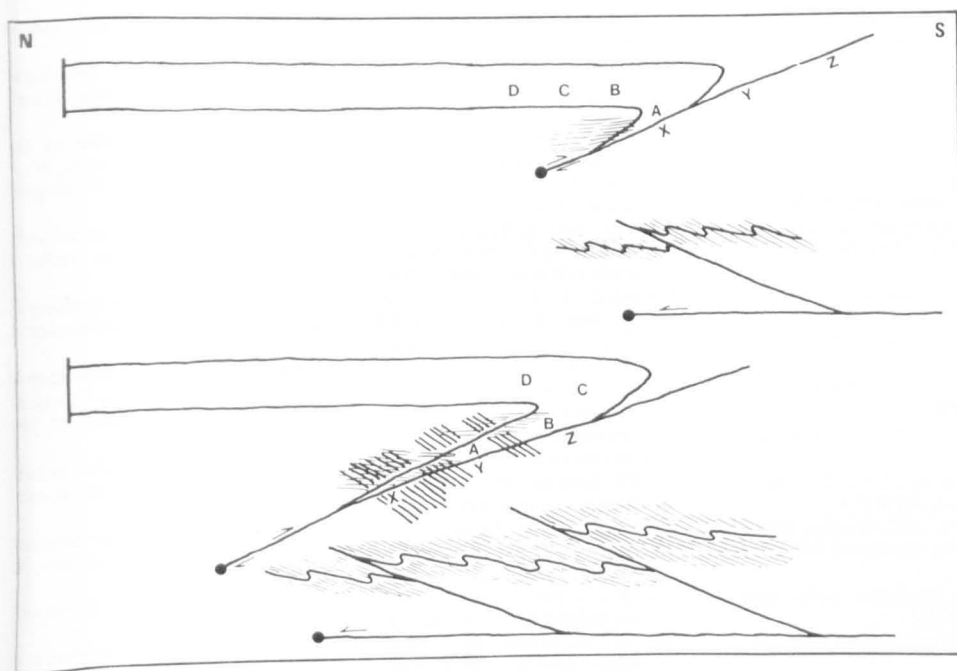


Fig. 17. This figure illustrates how movement along the major back-thrust occurs at a faster rate relative to the overturning of the overlying nappe pile (further explanation in the text). The diagram also shows how the cleavage of the south overprints the cleavage of the north, resulting in the formation of a southward dipping crenulation cleavage. A, B, C, D and X, Y, Z are reference points to demonstrate translations.

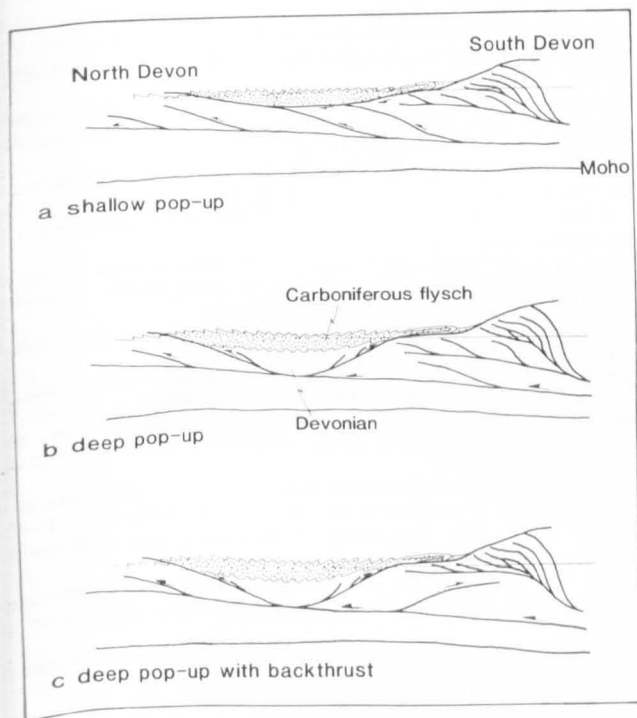


Fig. 18. Sections representing the possible deep structure of central SW England.

structures. The northward propagating structures underthrust the Upper Devonian and Lower Carboniferous unconsolidated foredeep flysch deposits which were in turn inverted. The rocks above the décollement were deformed into south-facing fold nappes of which the overturned limbs are exposed today. Where the southern zone underthrusts the northern zone, along the backthrust, overprinting of the northern structures by those of the south occurs gave rise to D2 structures which are most intense in the vicinity of the confrontation.

The models involving backthrusting to the south (Shackleton *et al.* 1982; Coward & Smallwood 1984) are essentially correct and we endorse them. Also the structural zones proposed by Sanderson & Dearman (1973) and Hobson & Sanderson (1983), although simplistic and not relating specifically to the nappe structure of the region, are still broadly applicable. We believe that the detailed biostratigraphical and lithostratigraphical observations of Isaac *et al.* (1983) and Selwood & Thomas (1986, 1988) could be integrated into such tectonic models.

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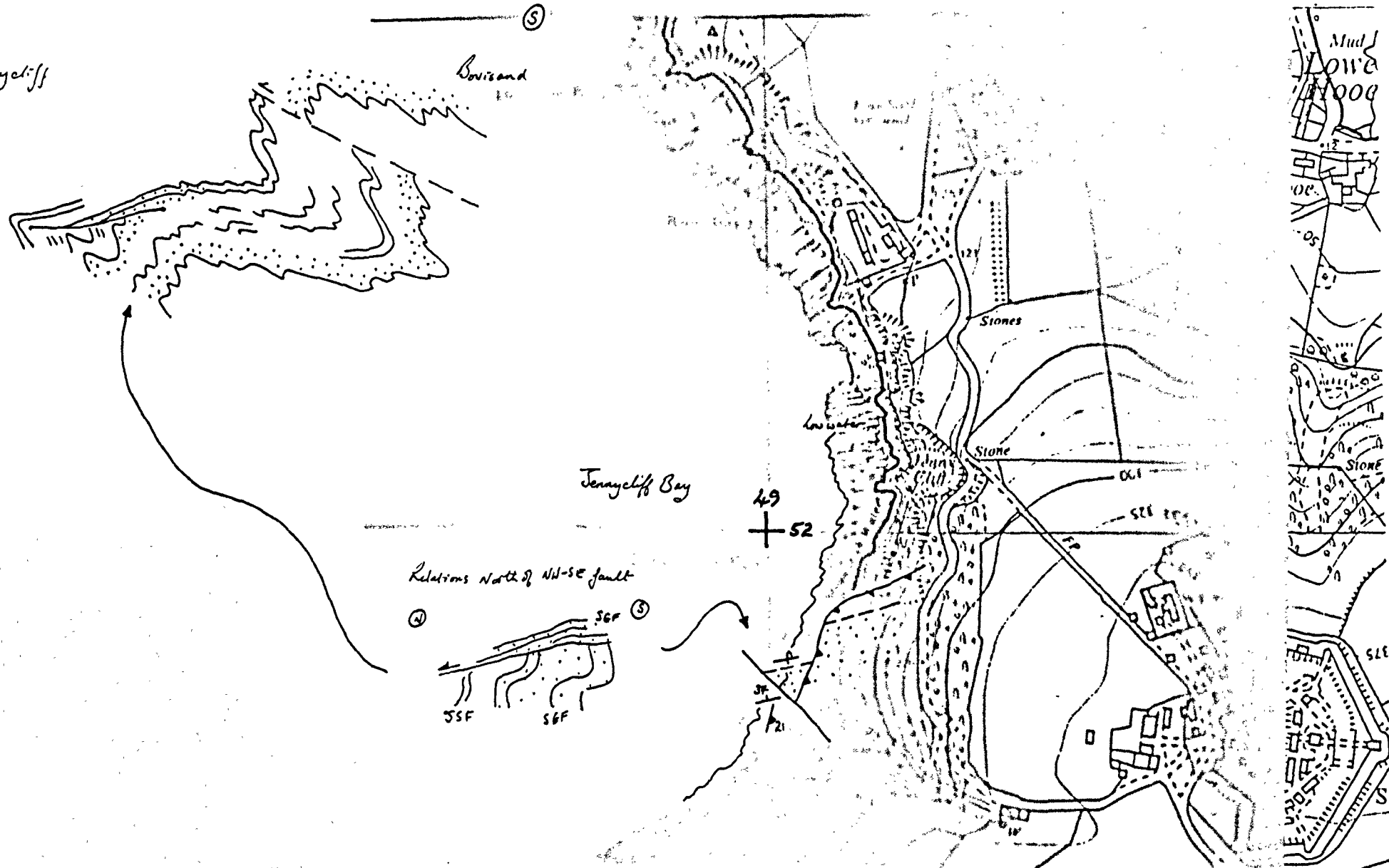
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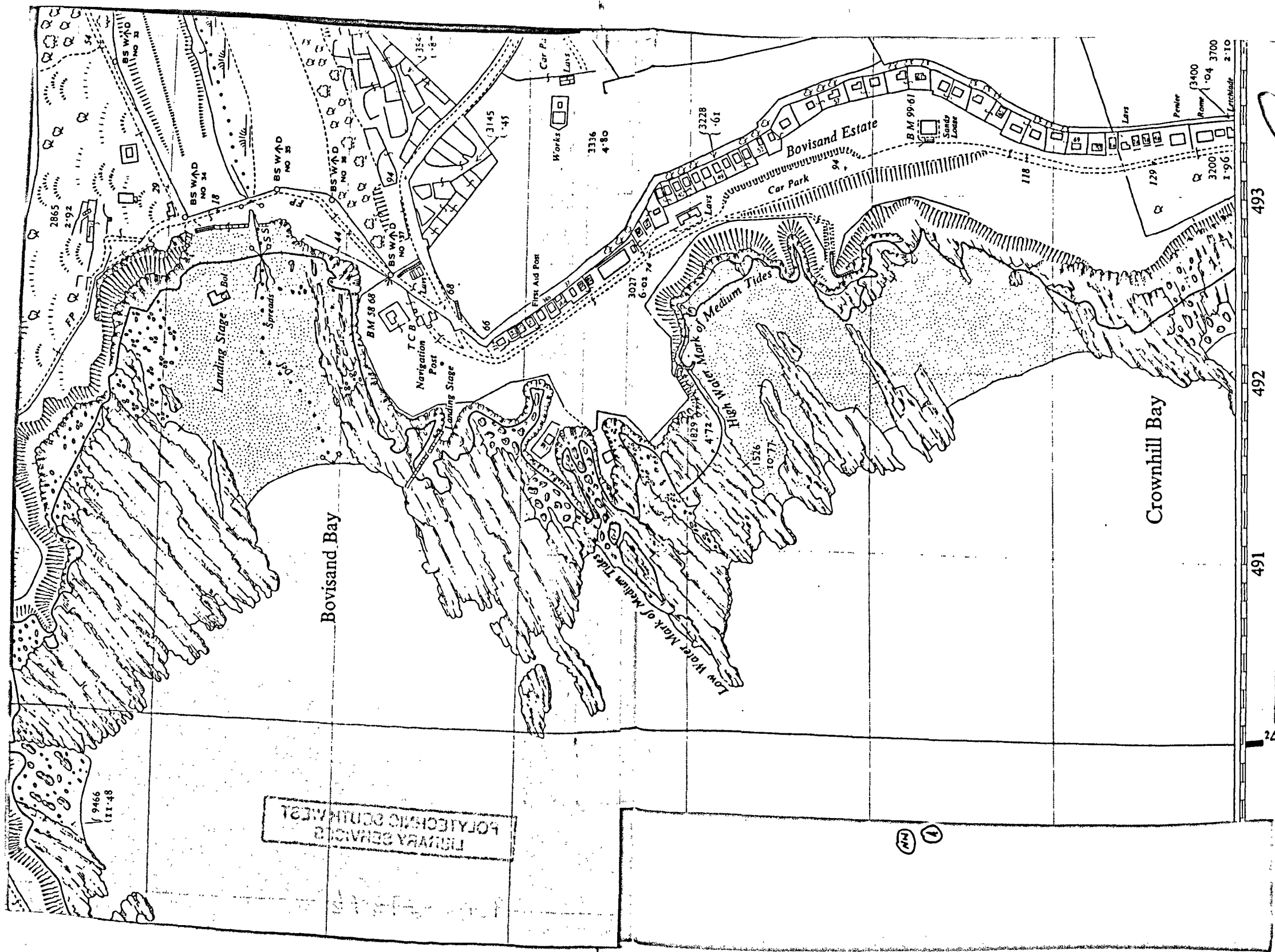


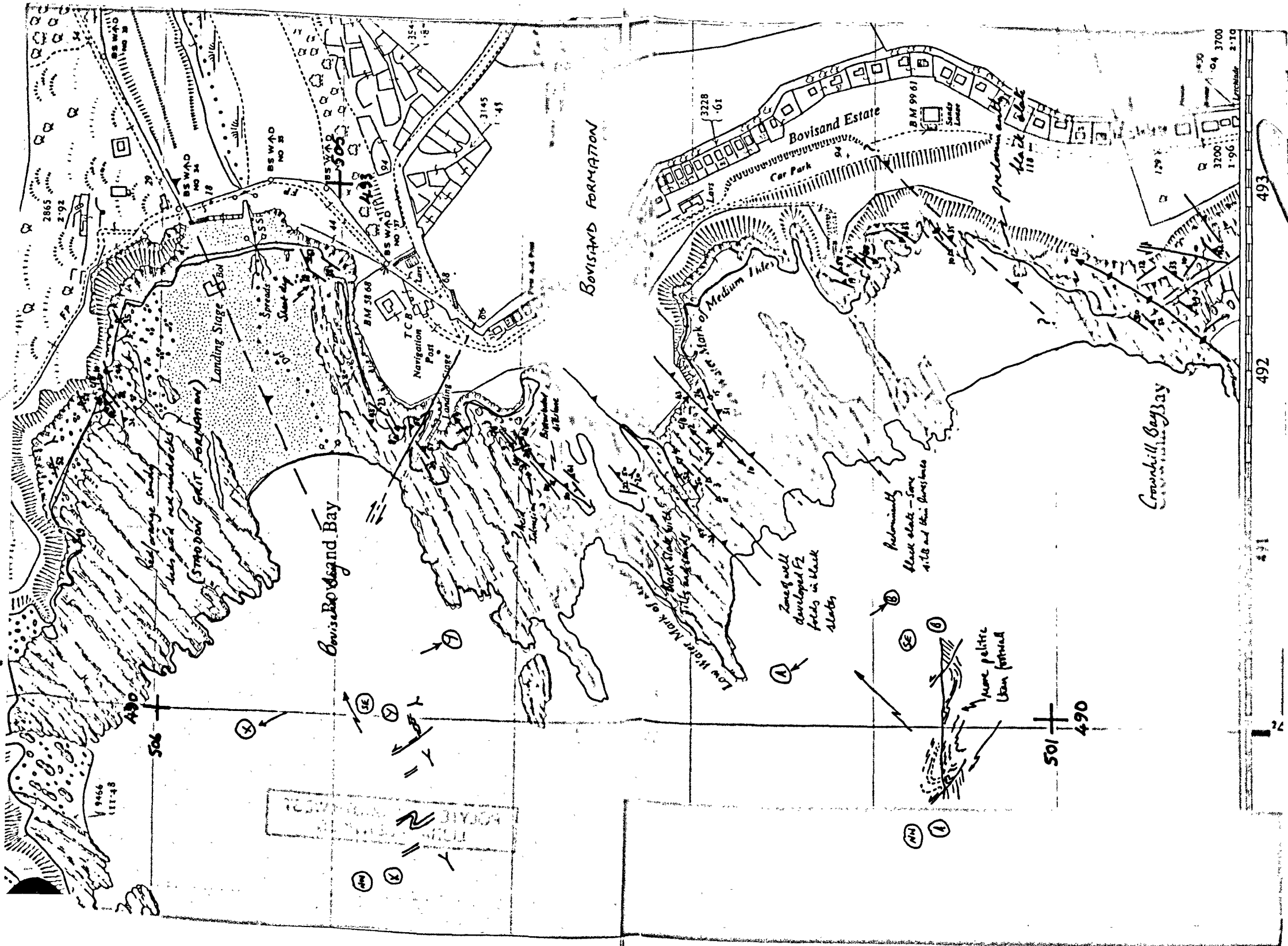
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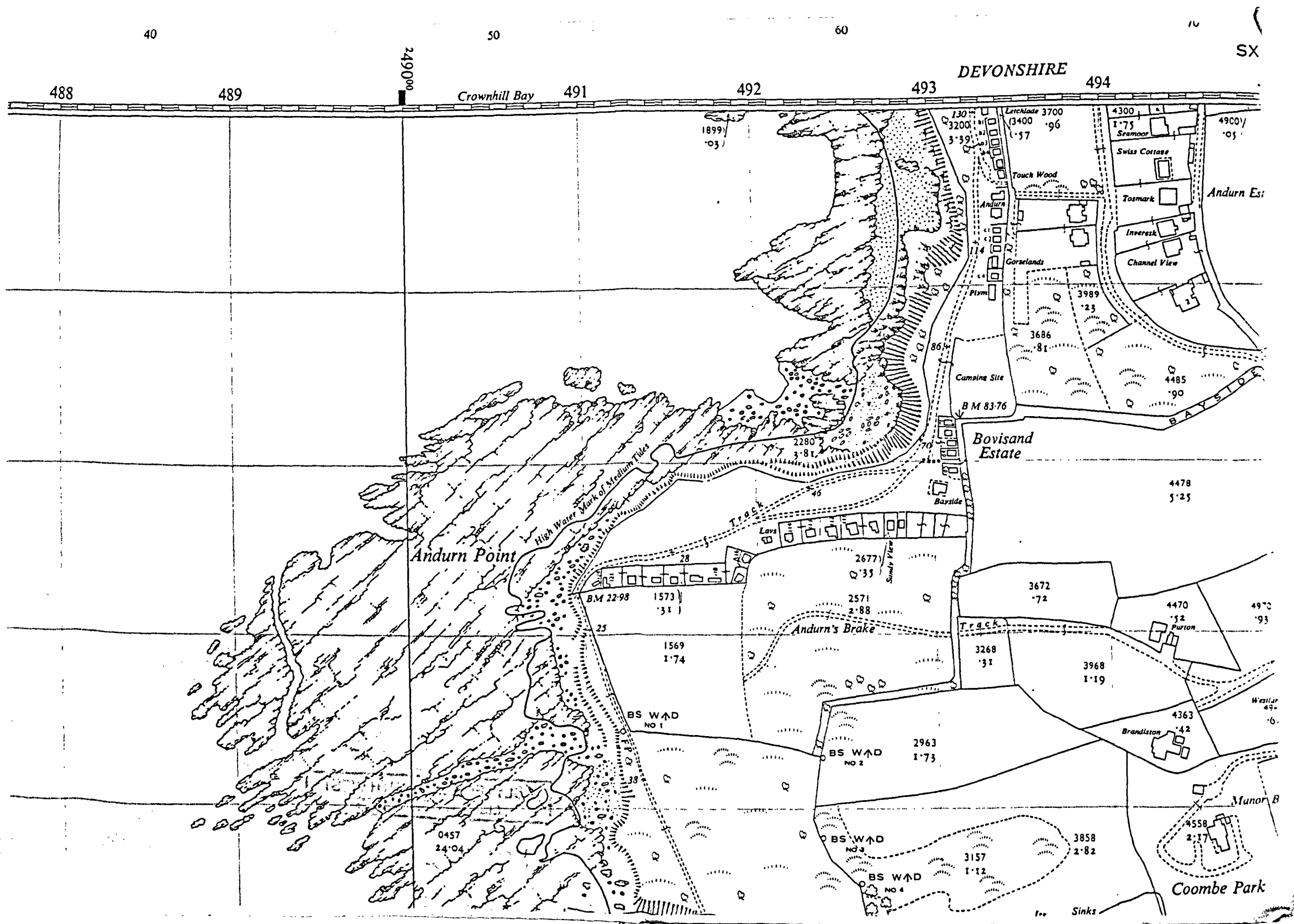


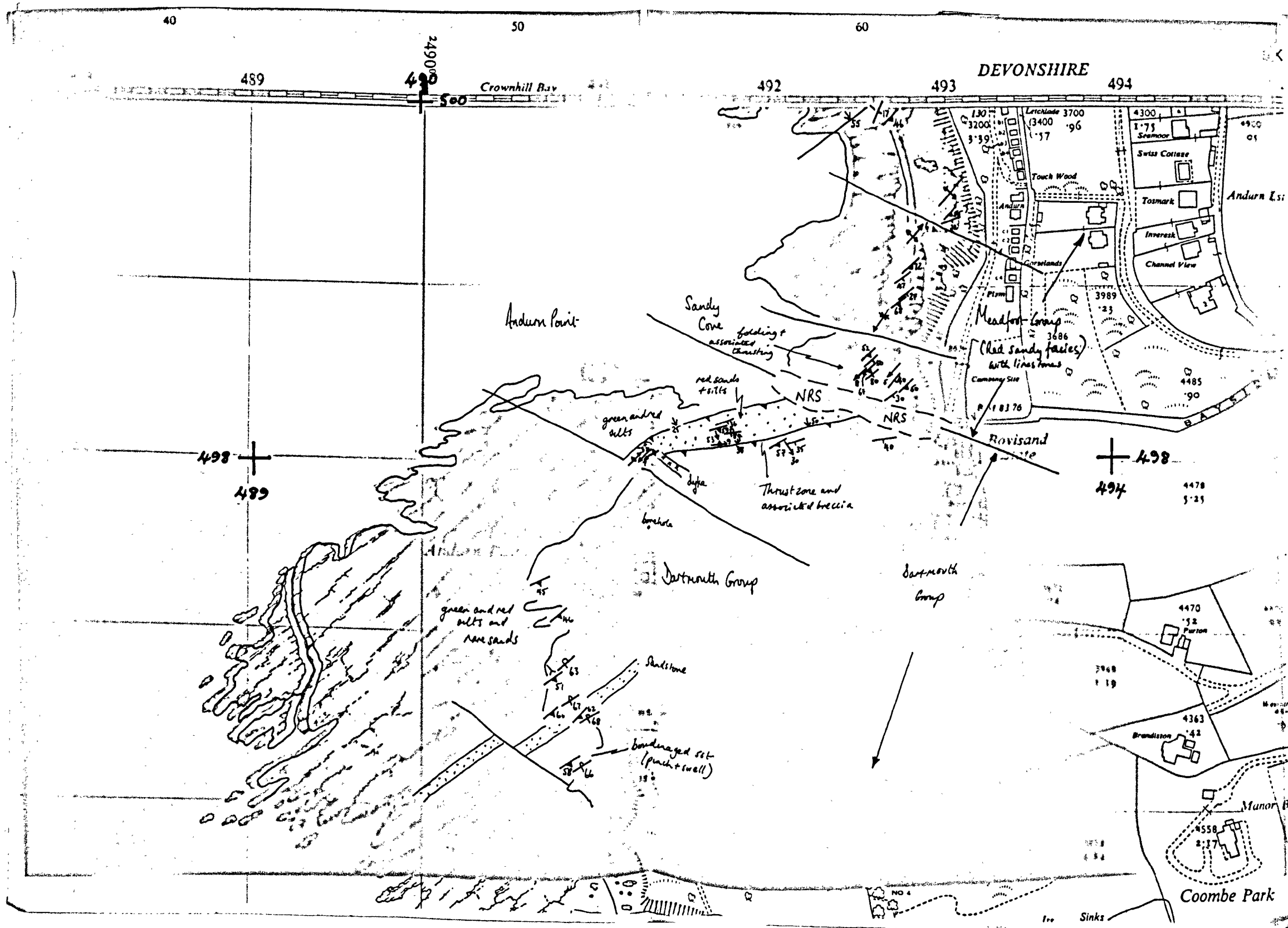
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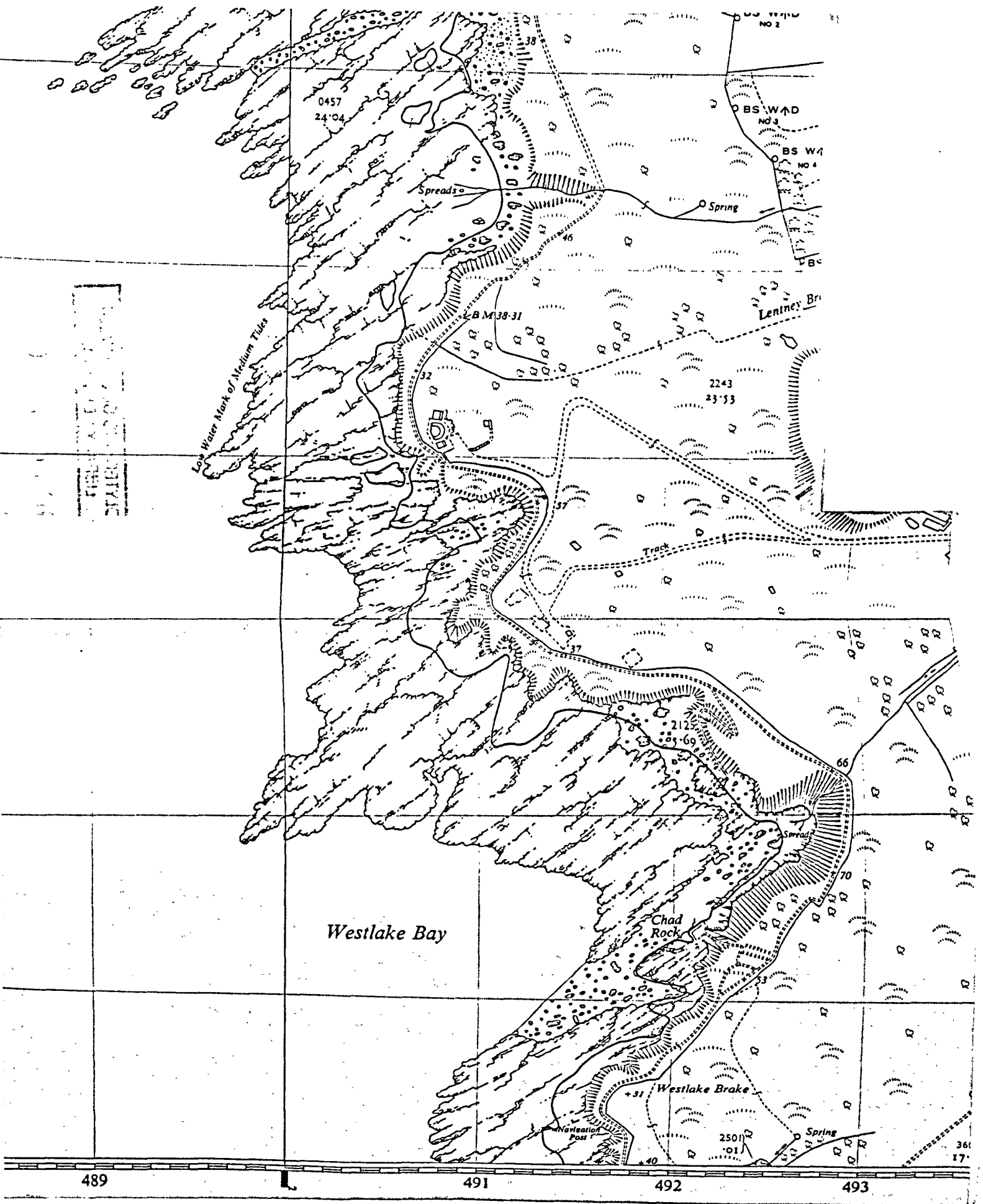


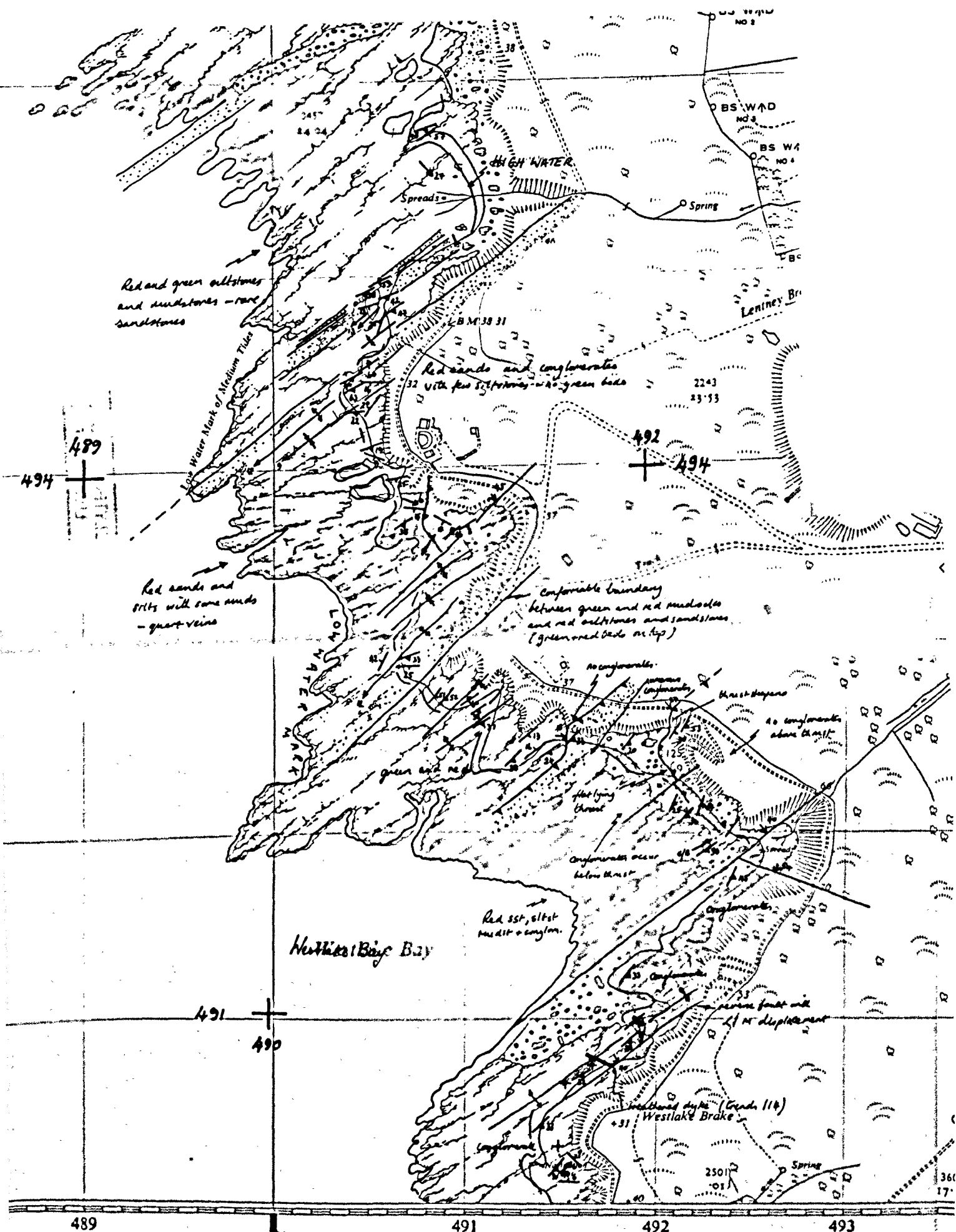
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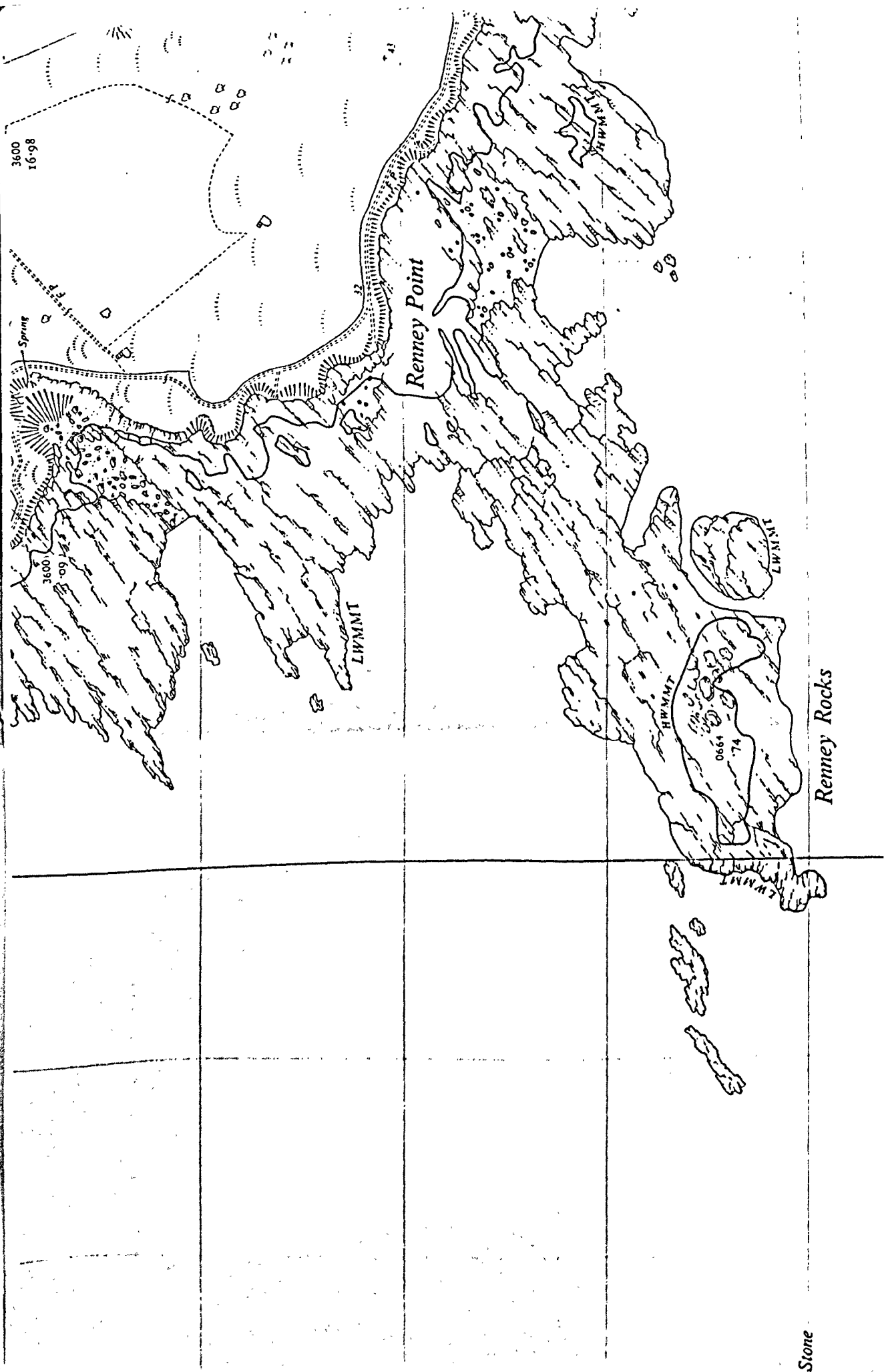


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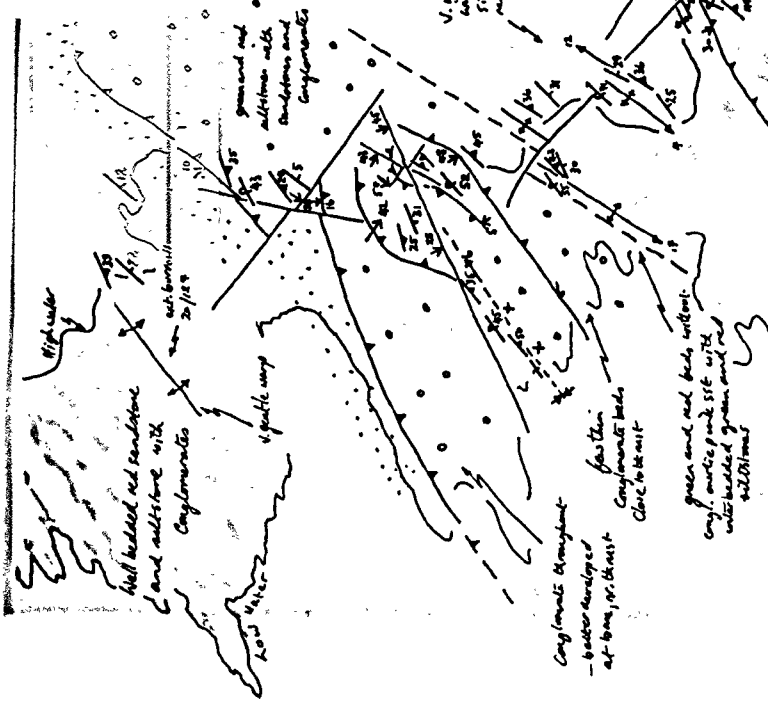
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Heavily eroded sandstones (with gorges)

Much Quartz Veining throughout all sandstones

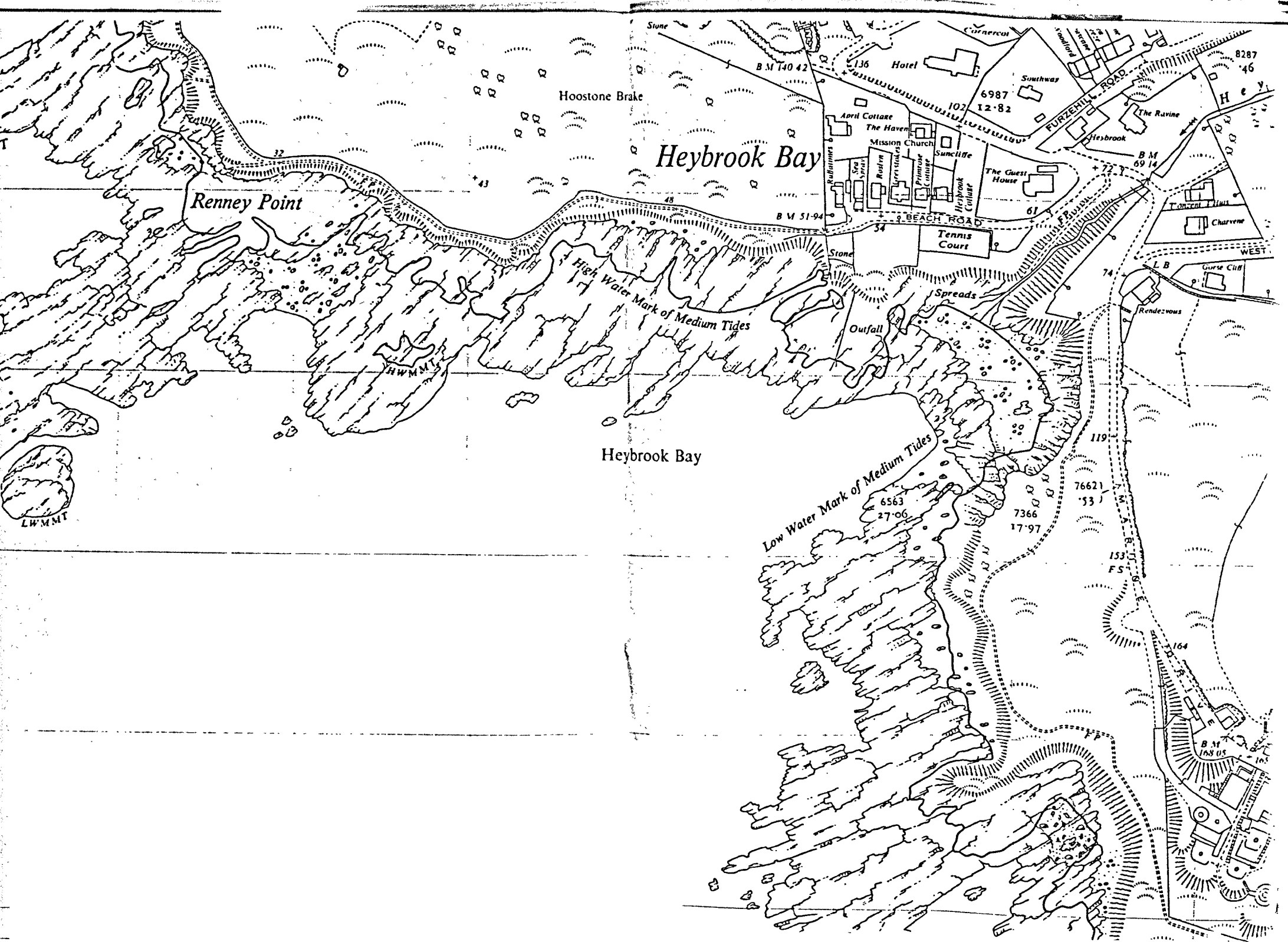
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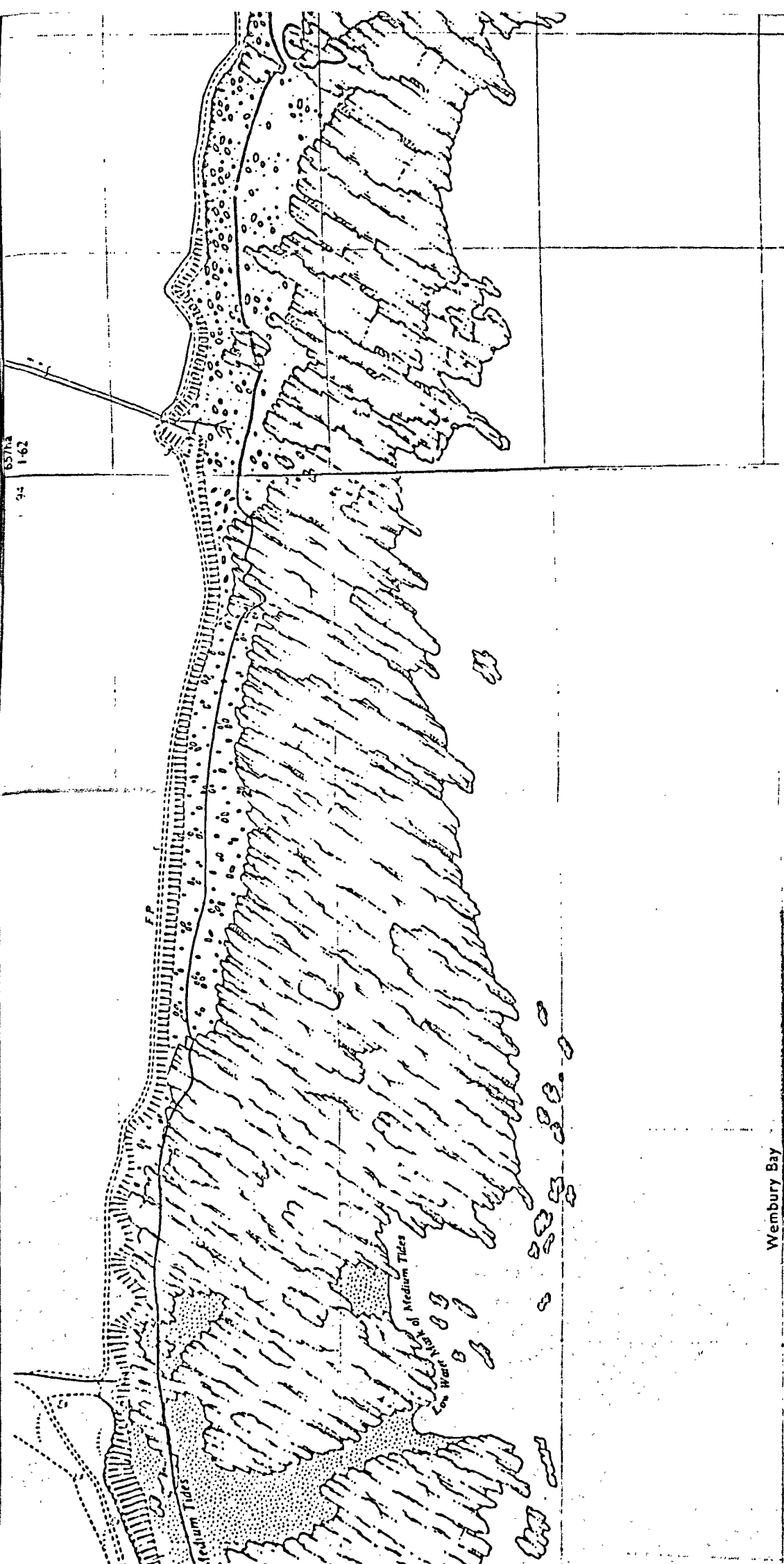
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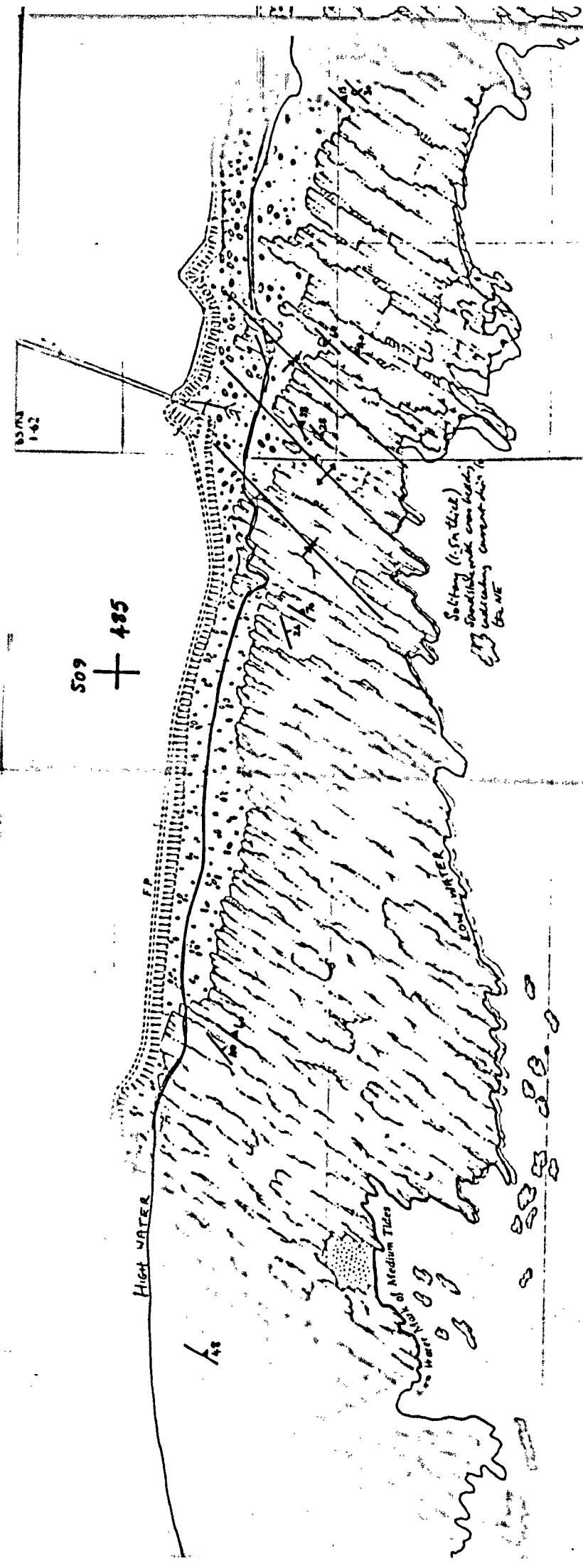
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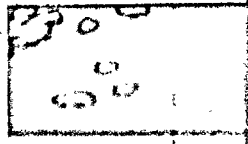
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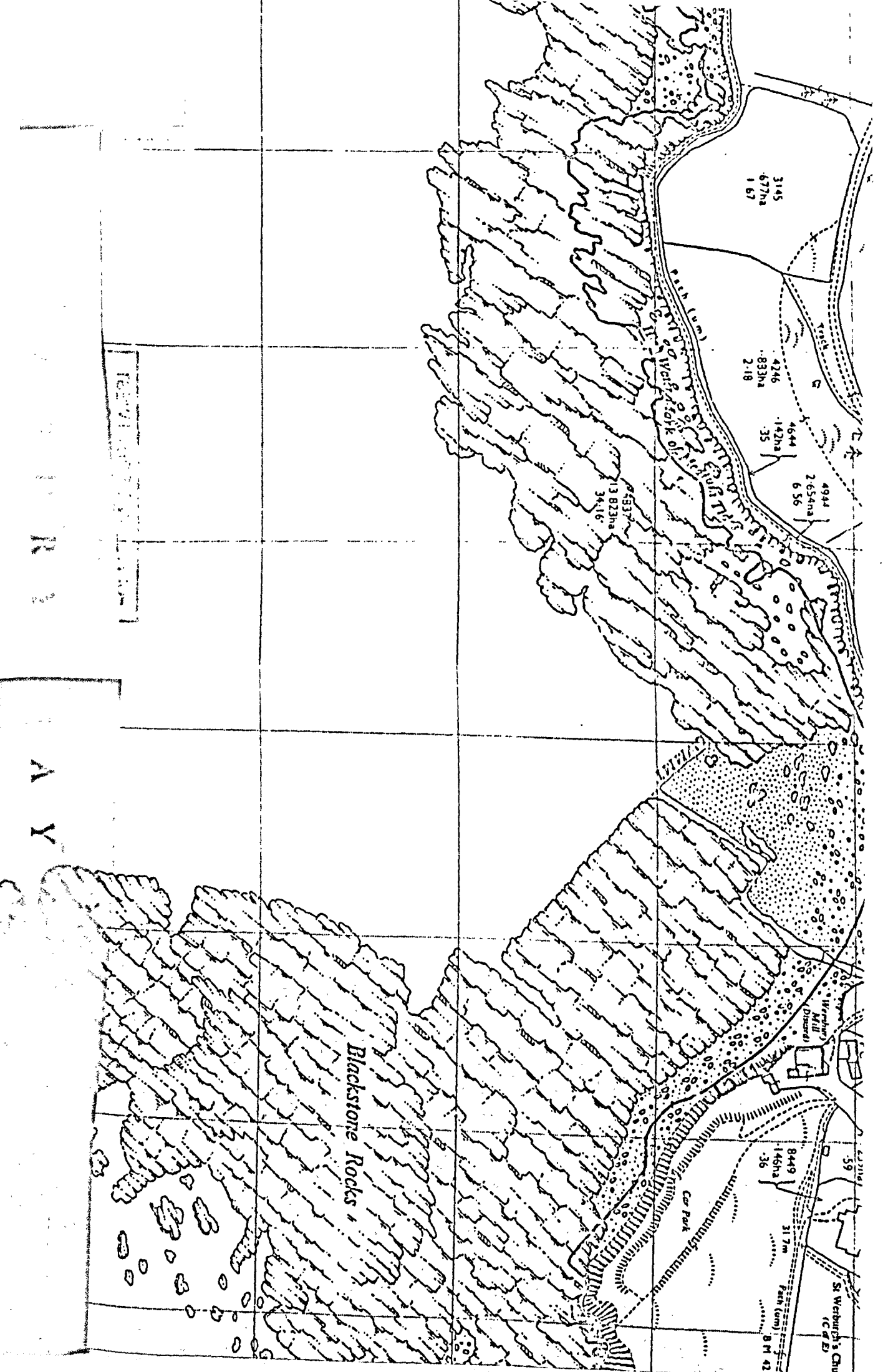
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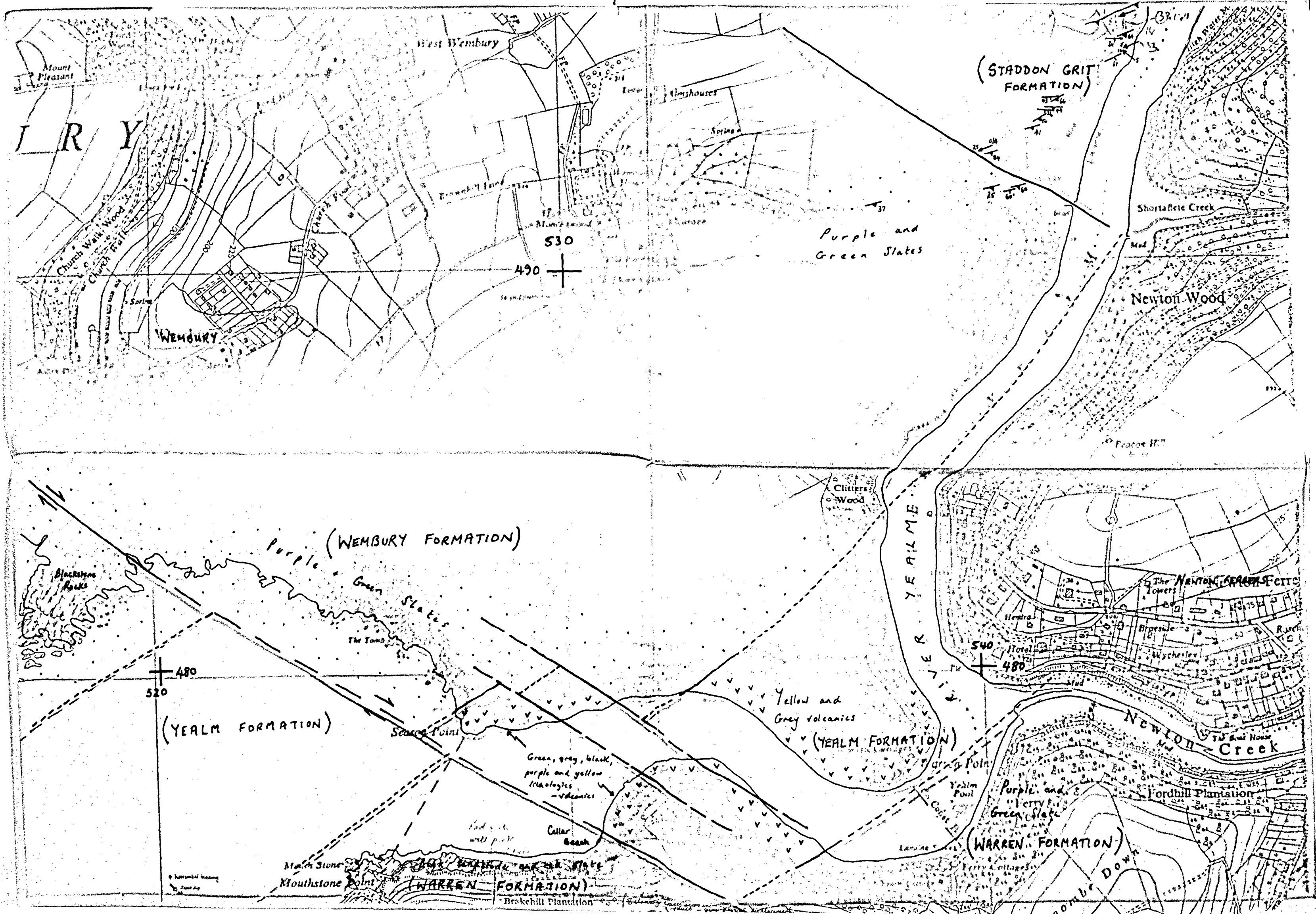
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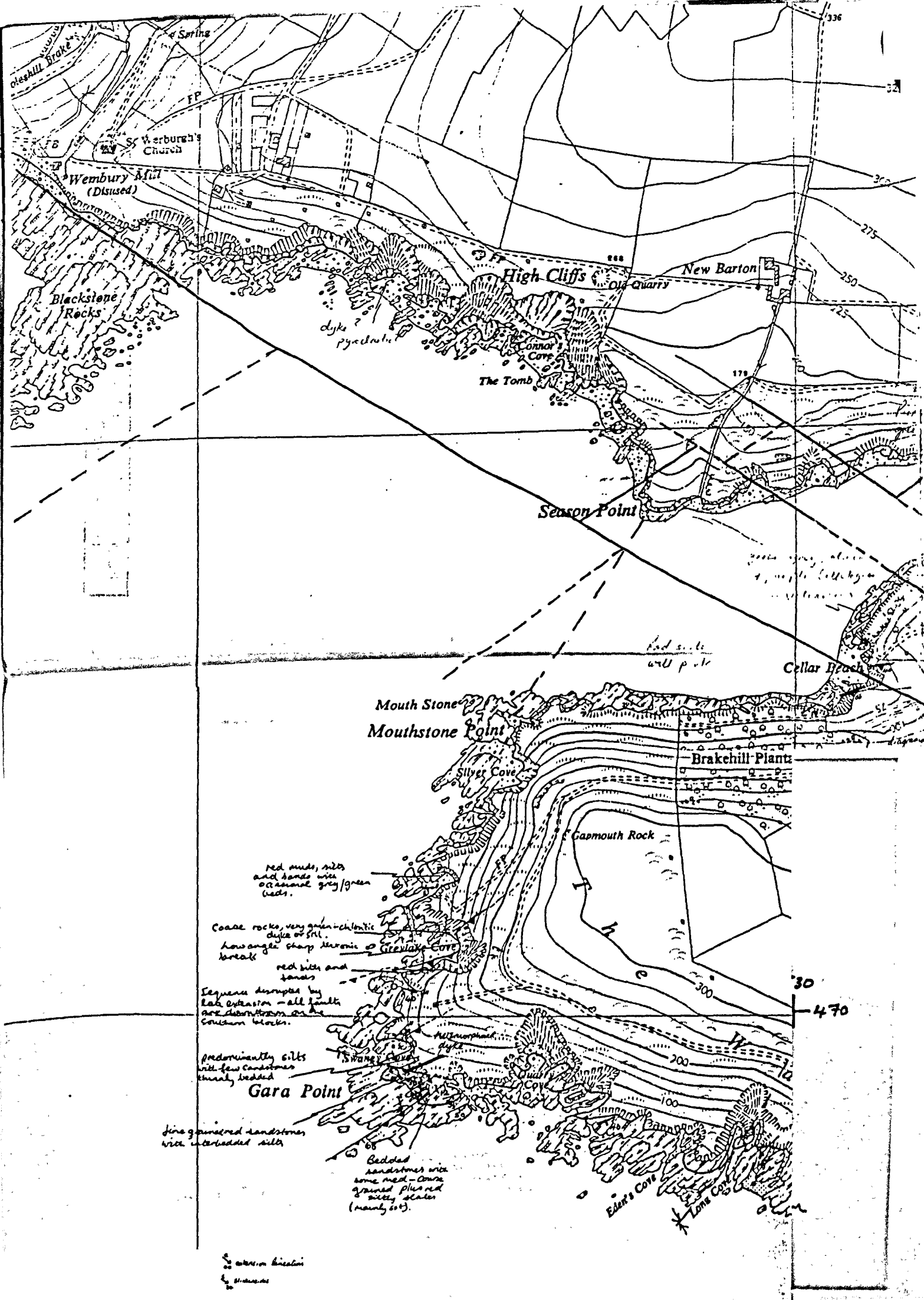


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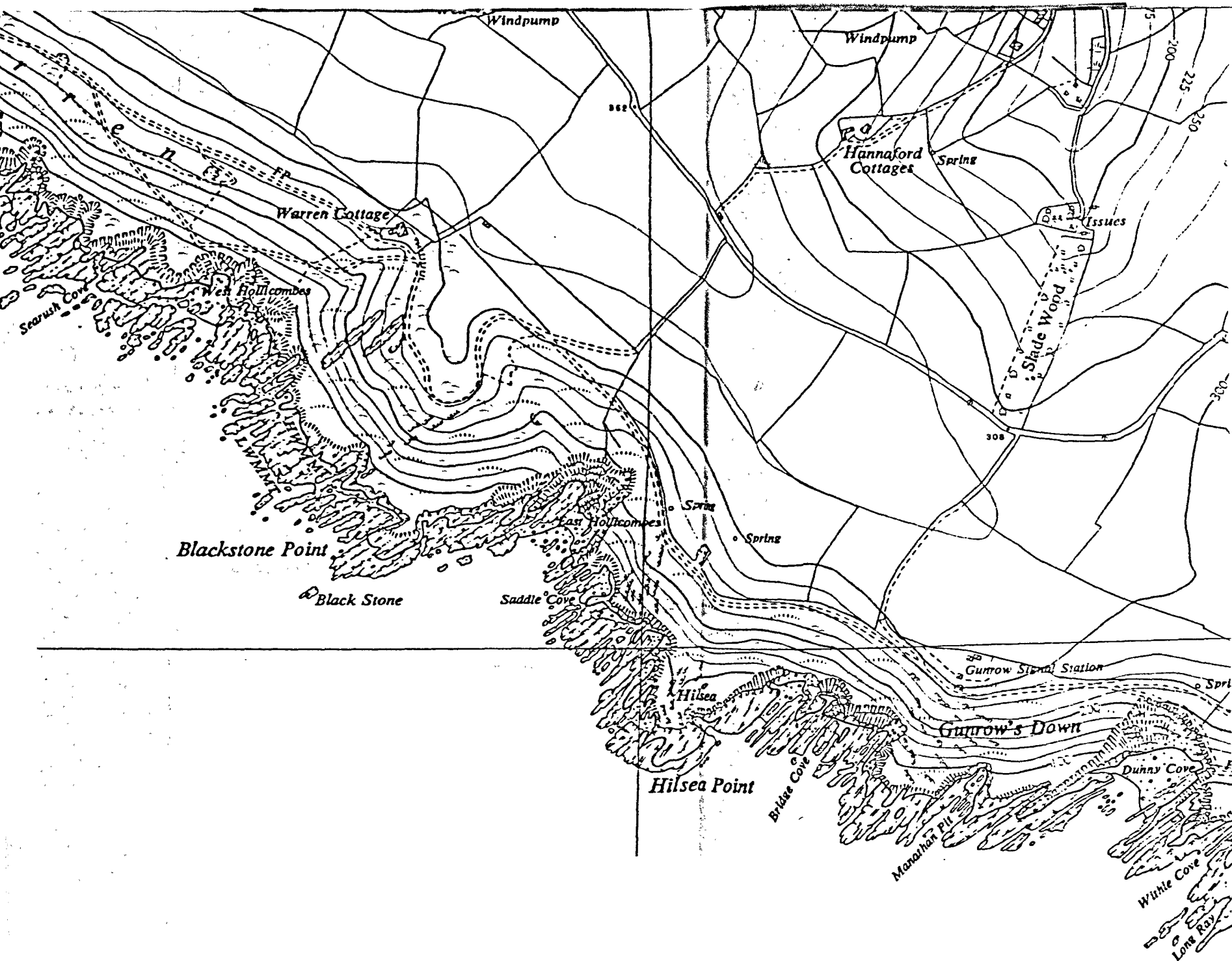


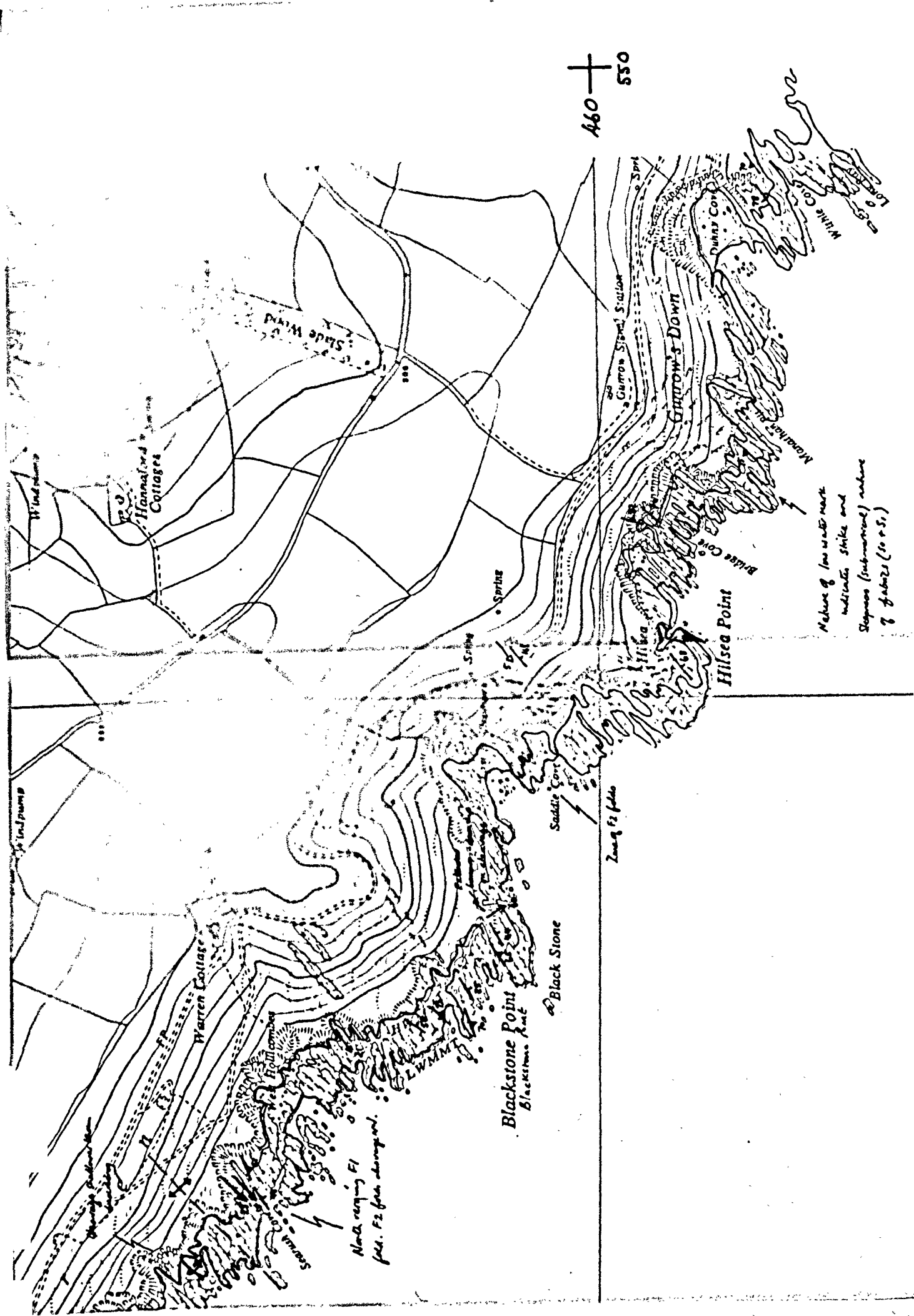
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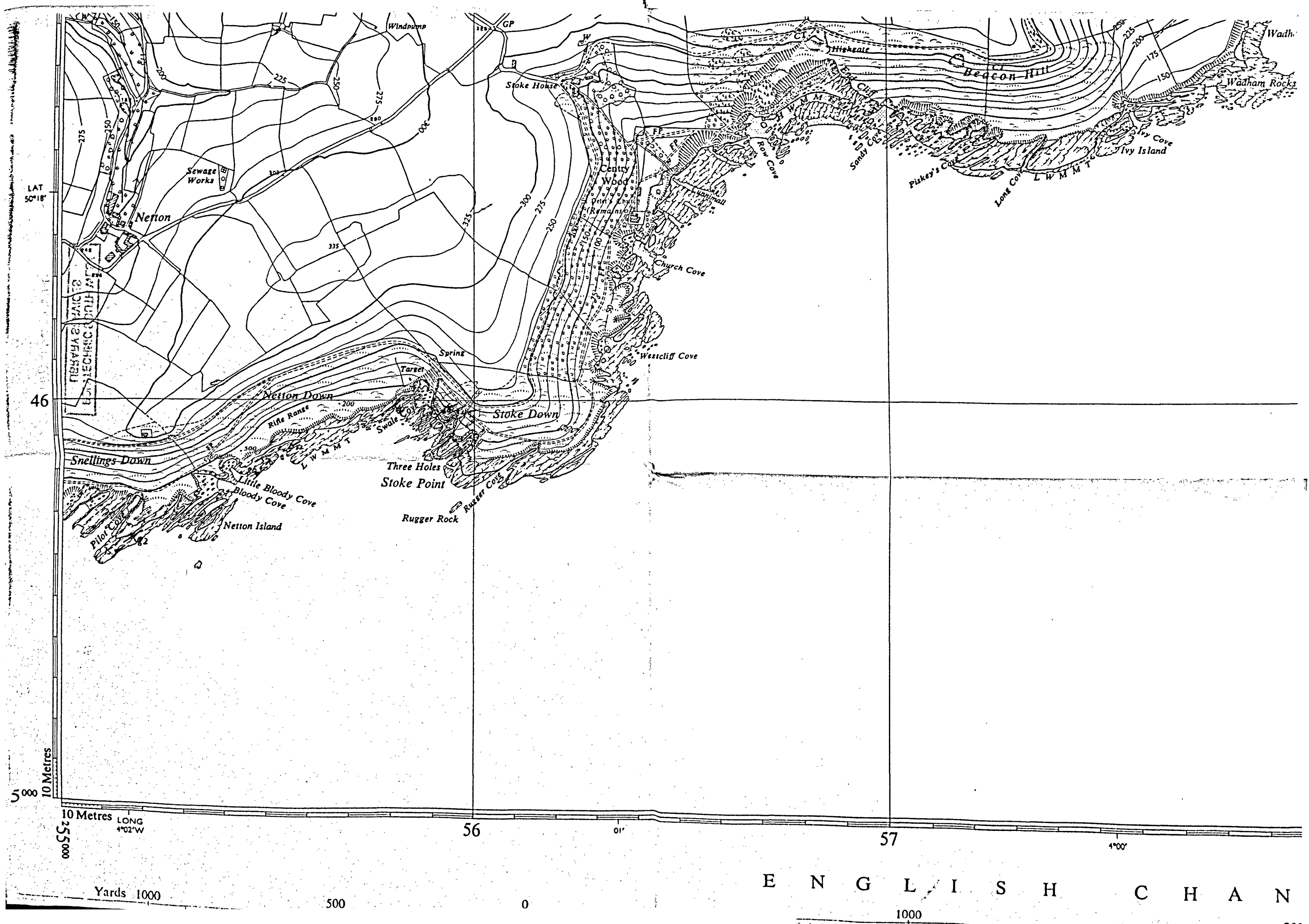


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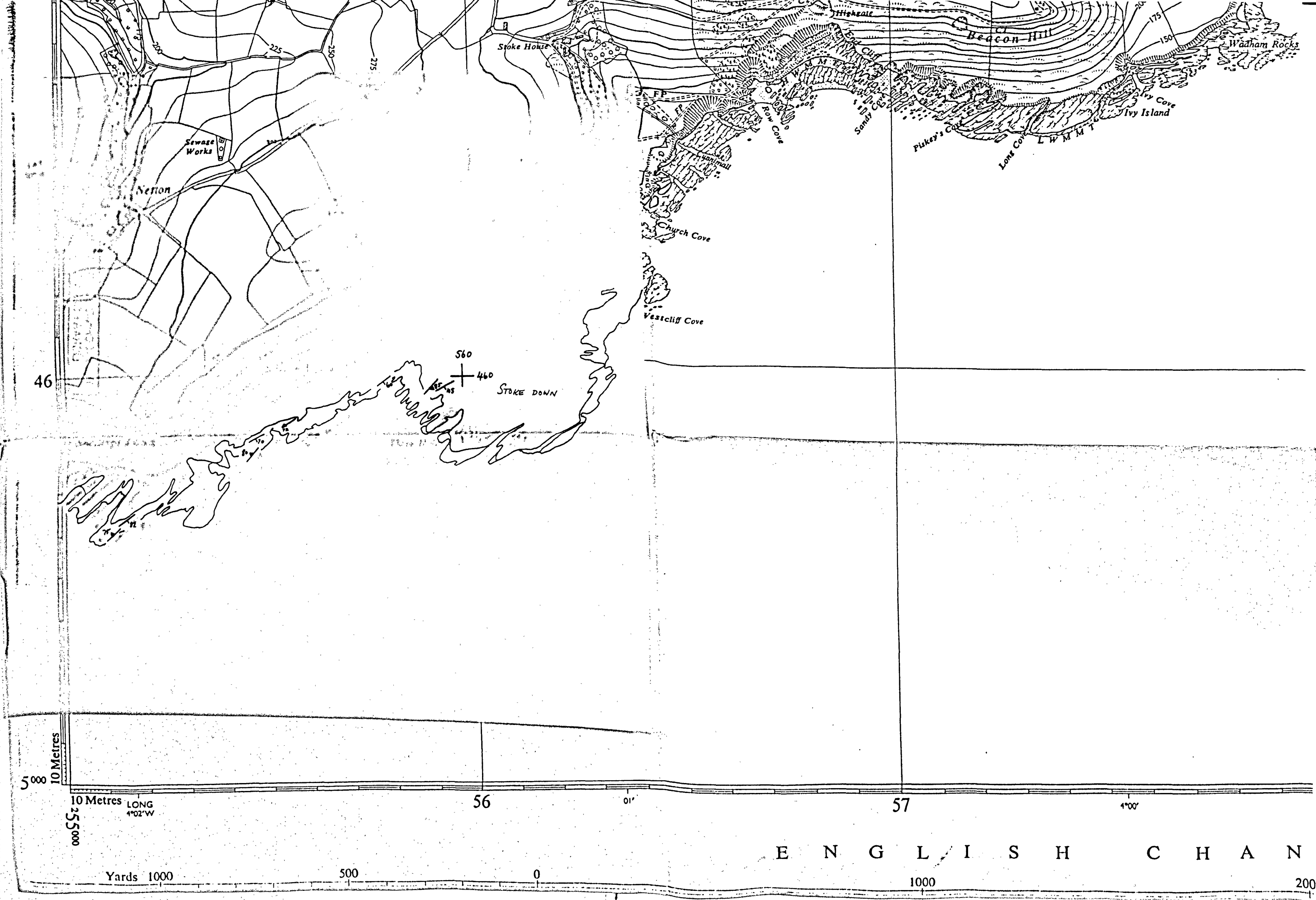
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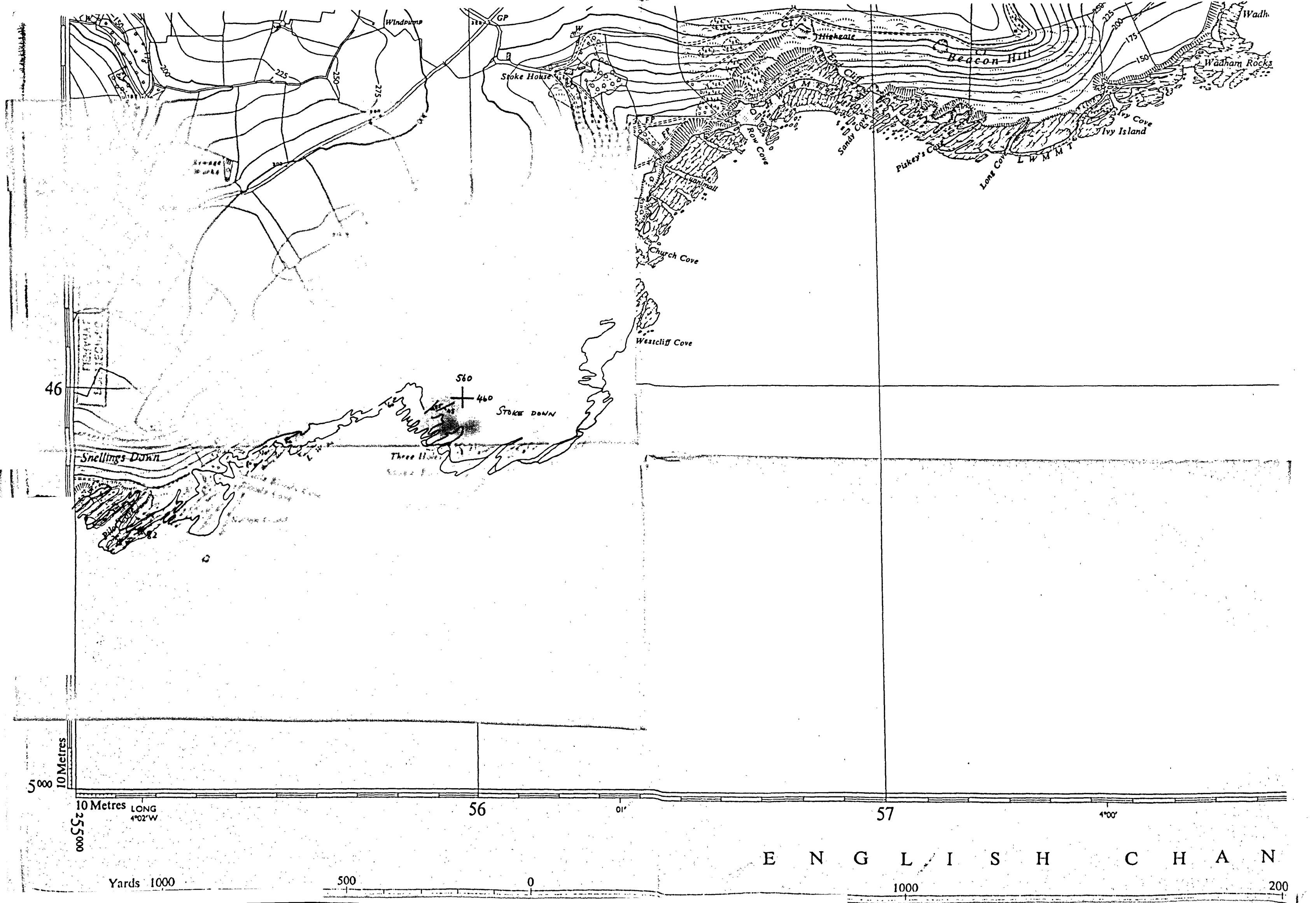
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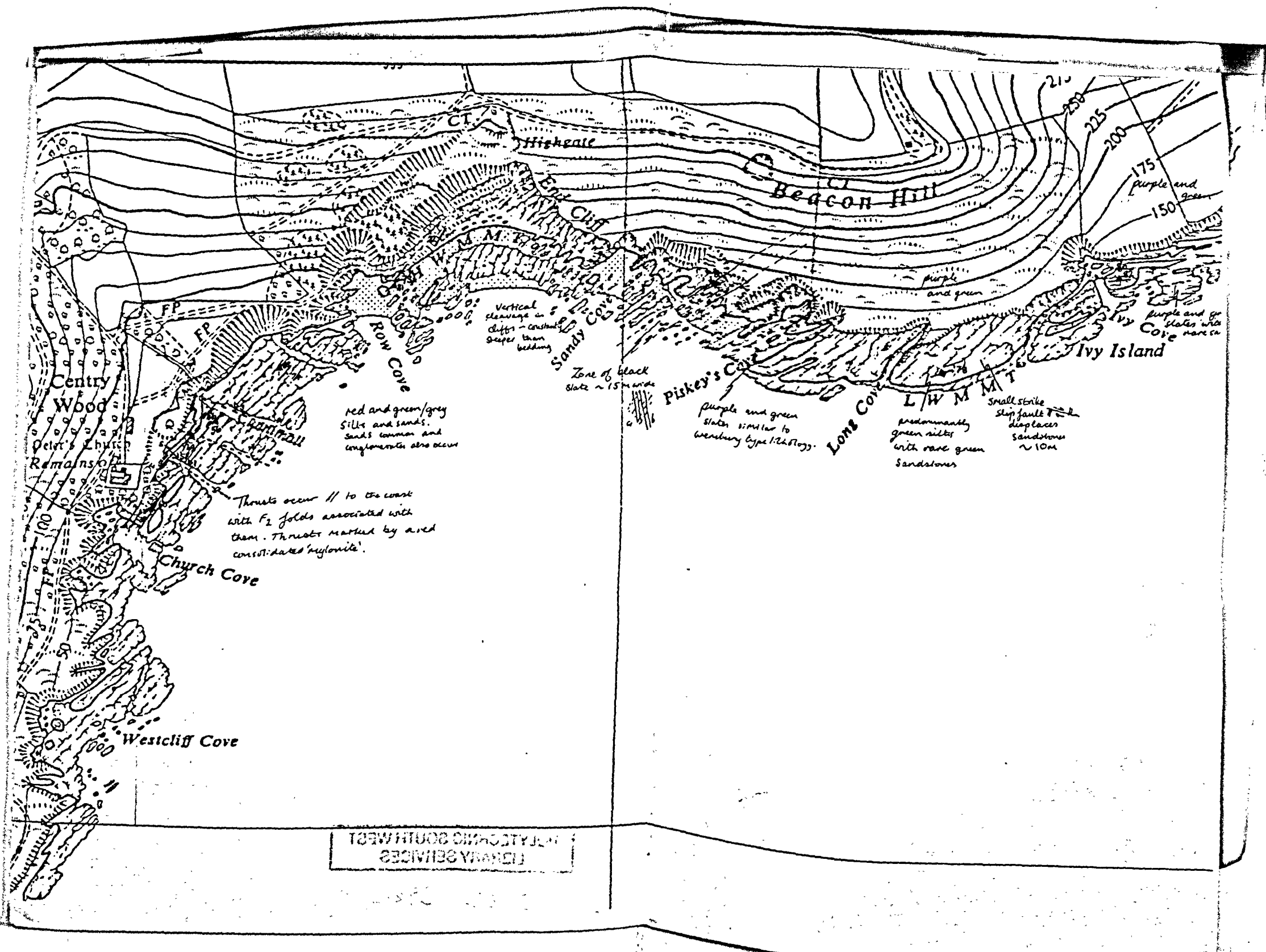


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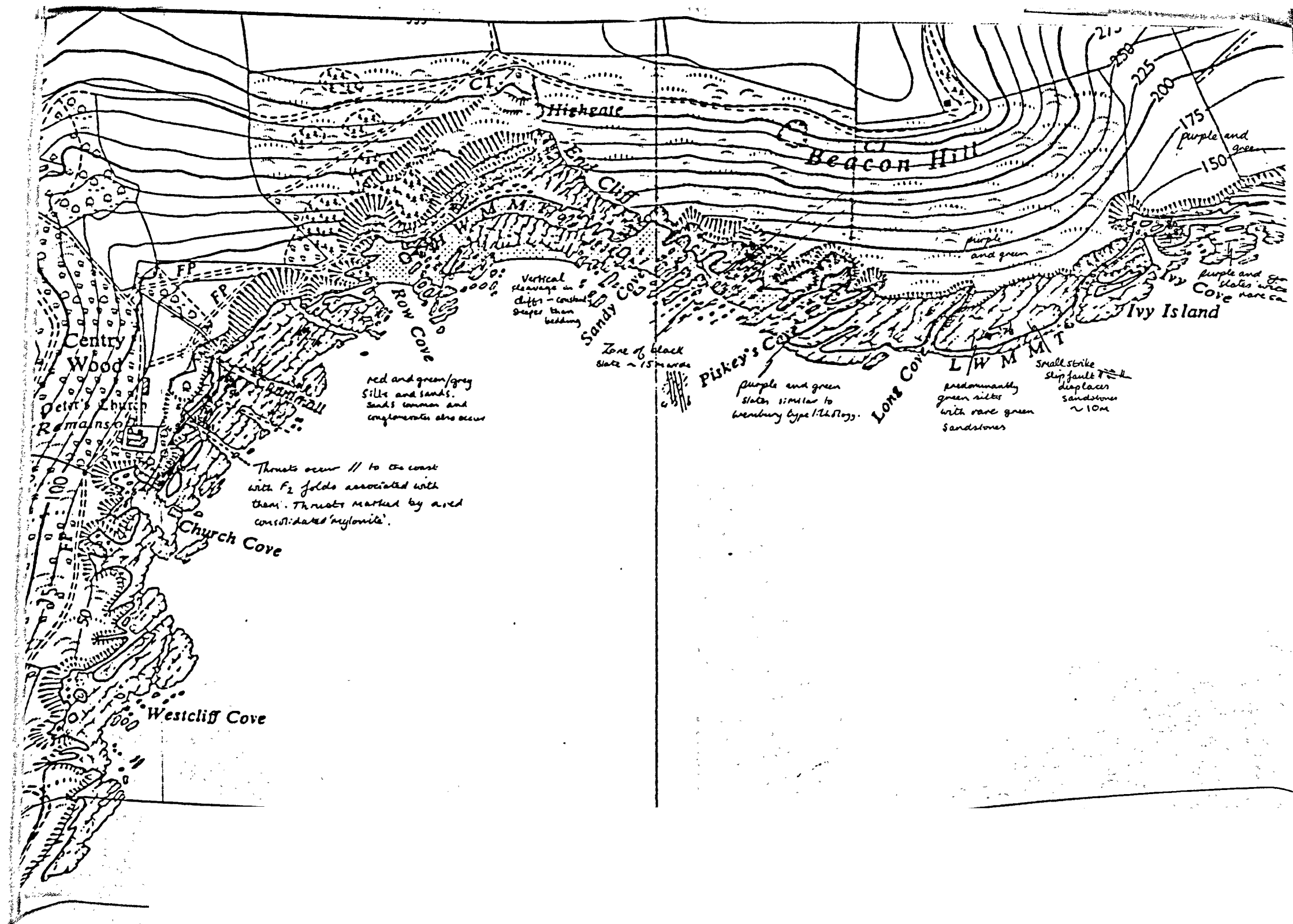
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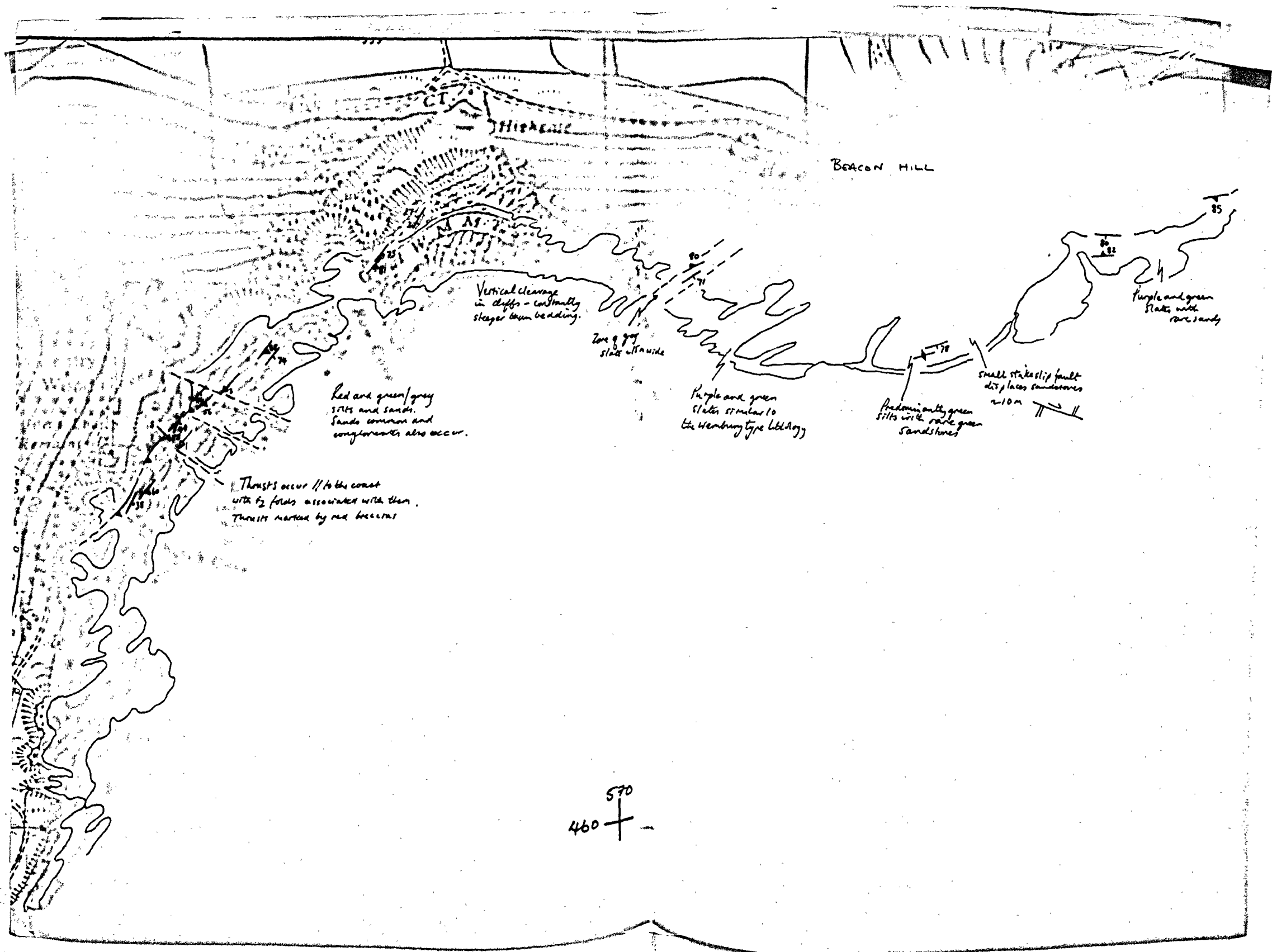
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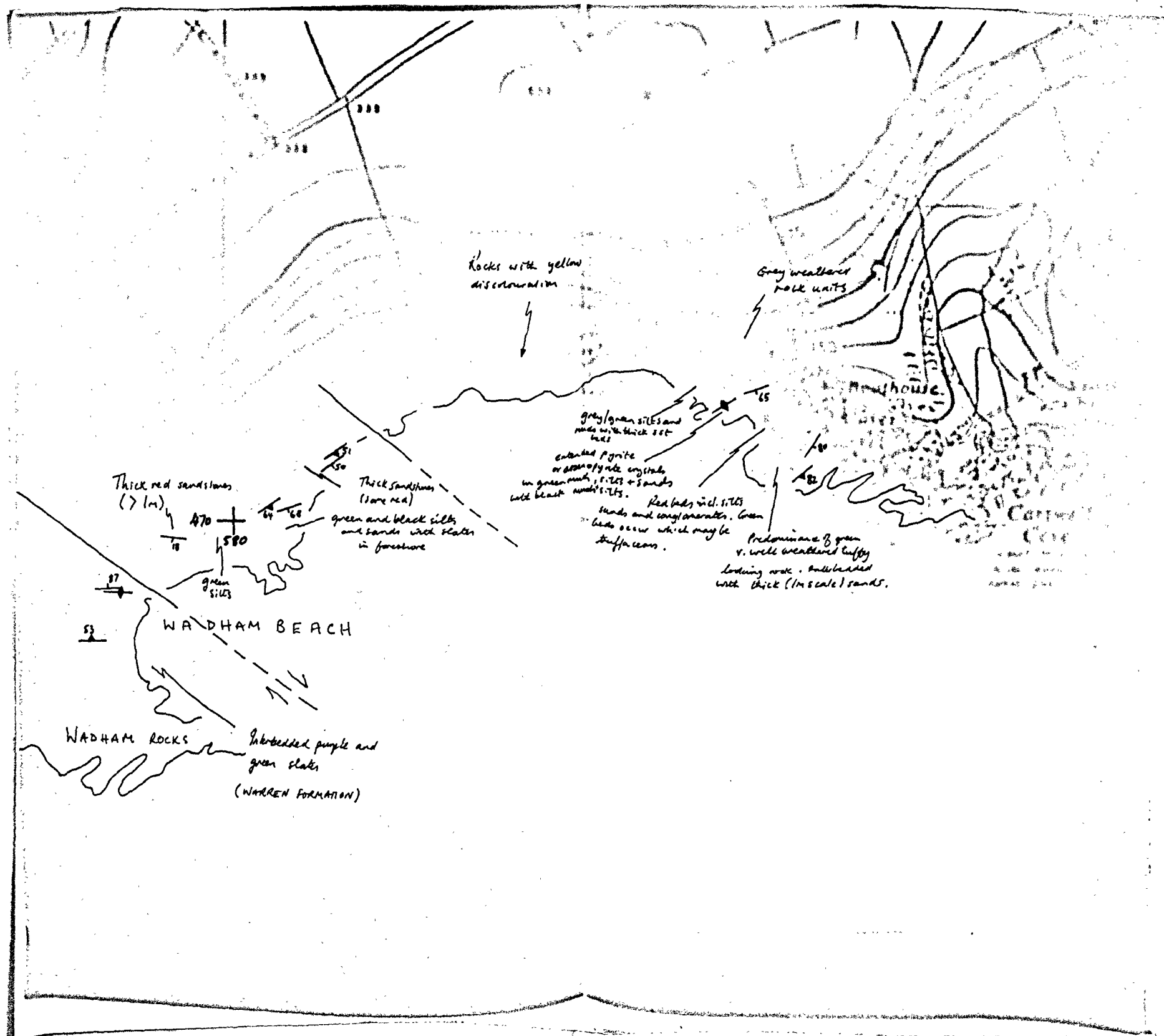


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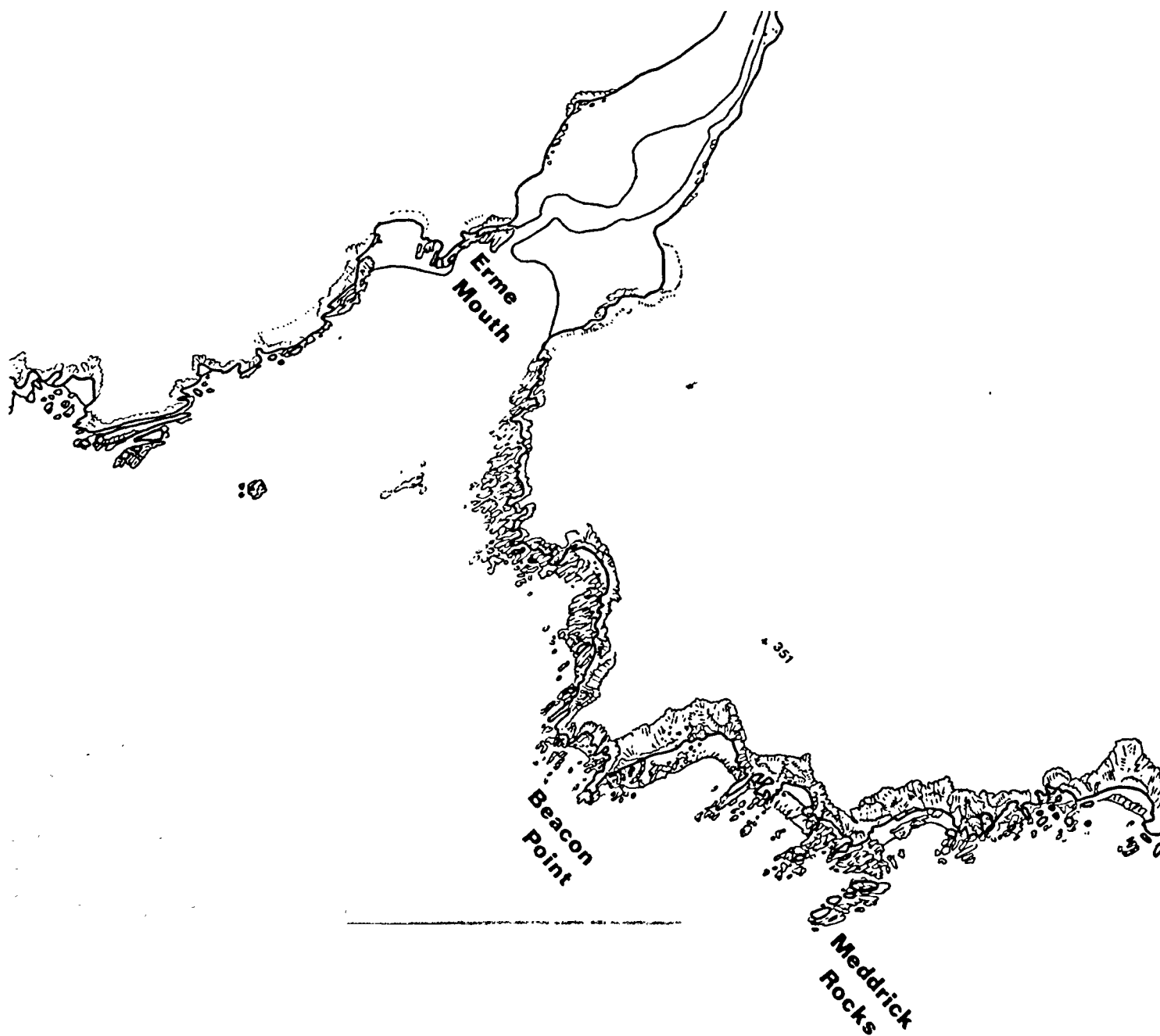


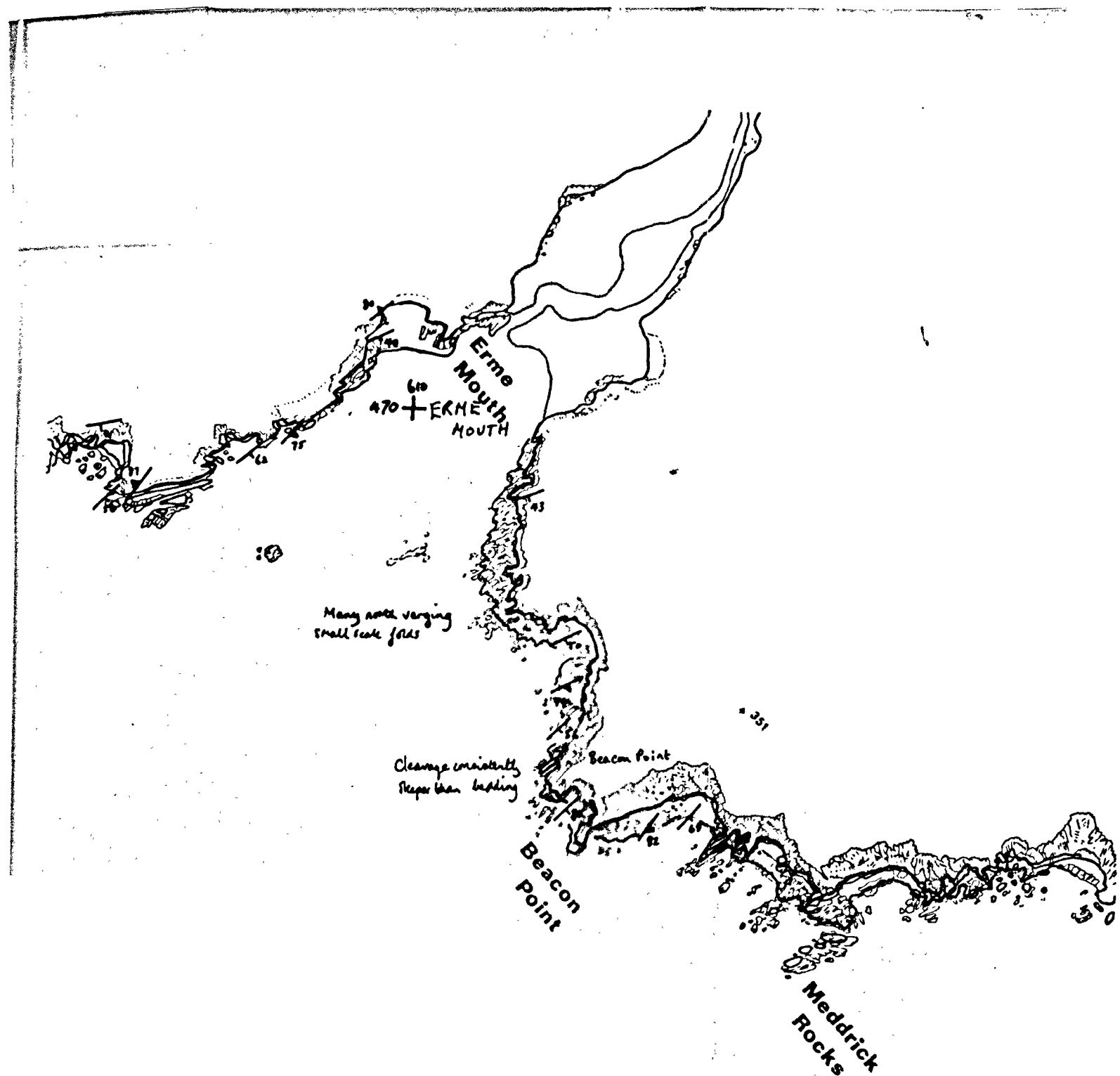
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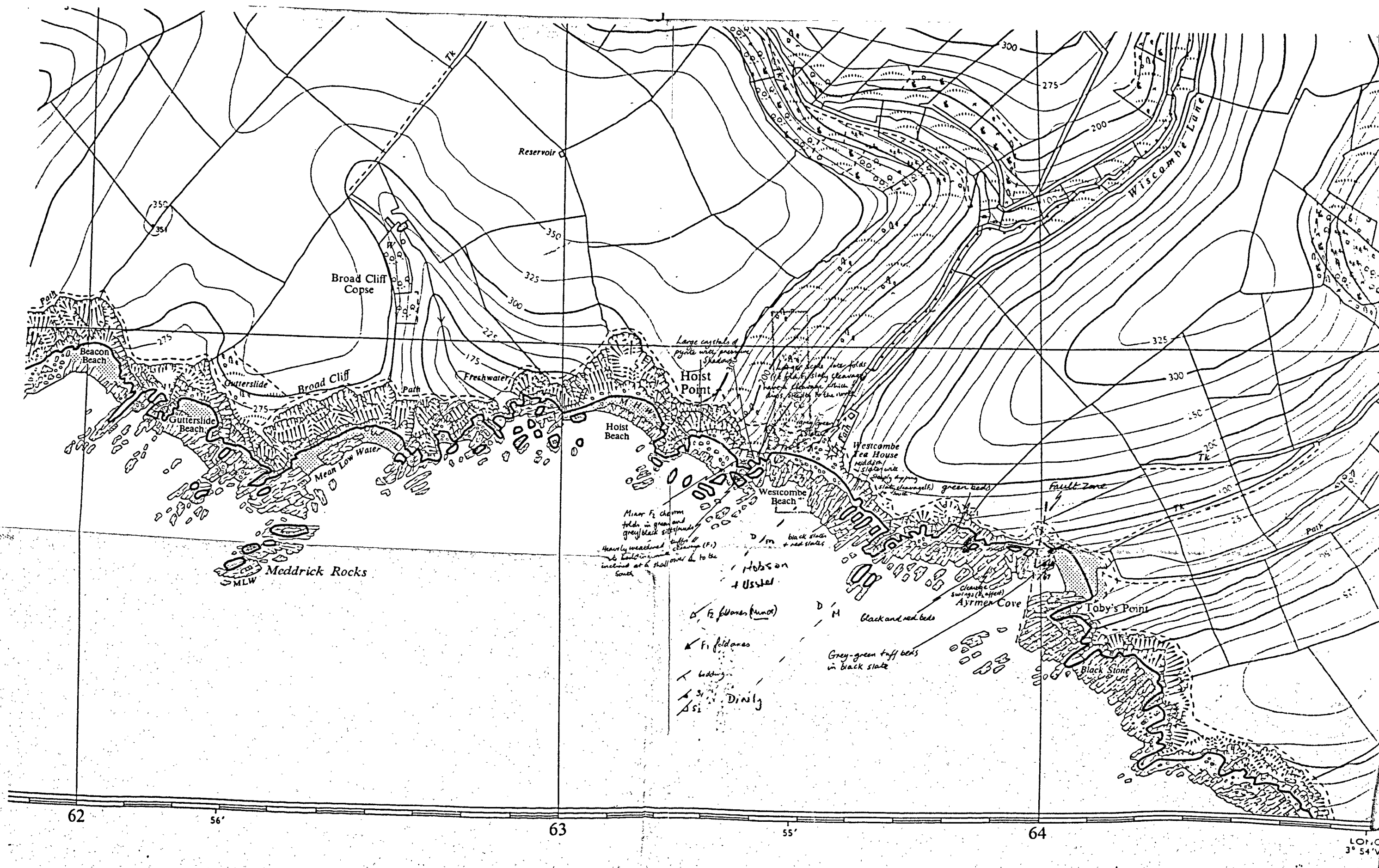


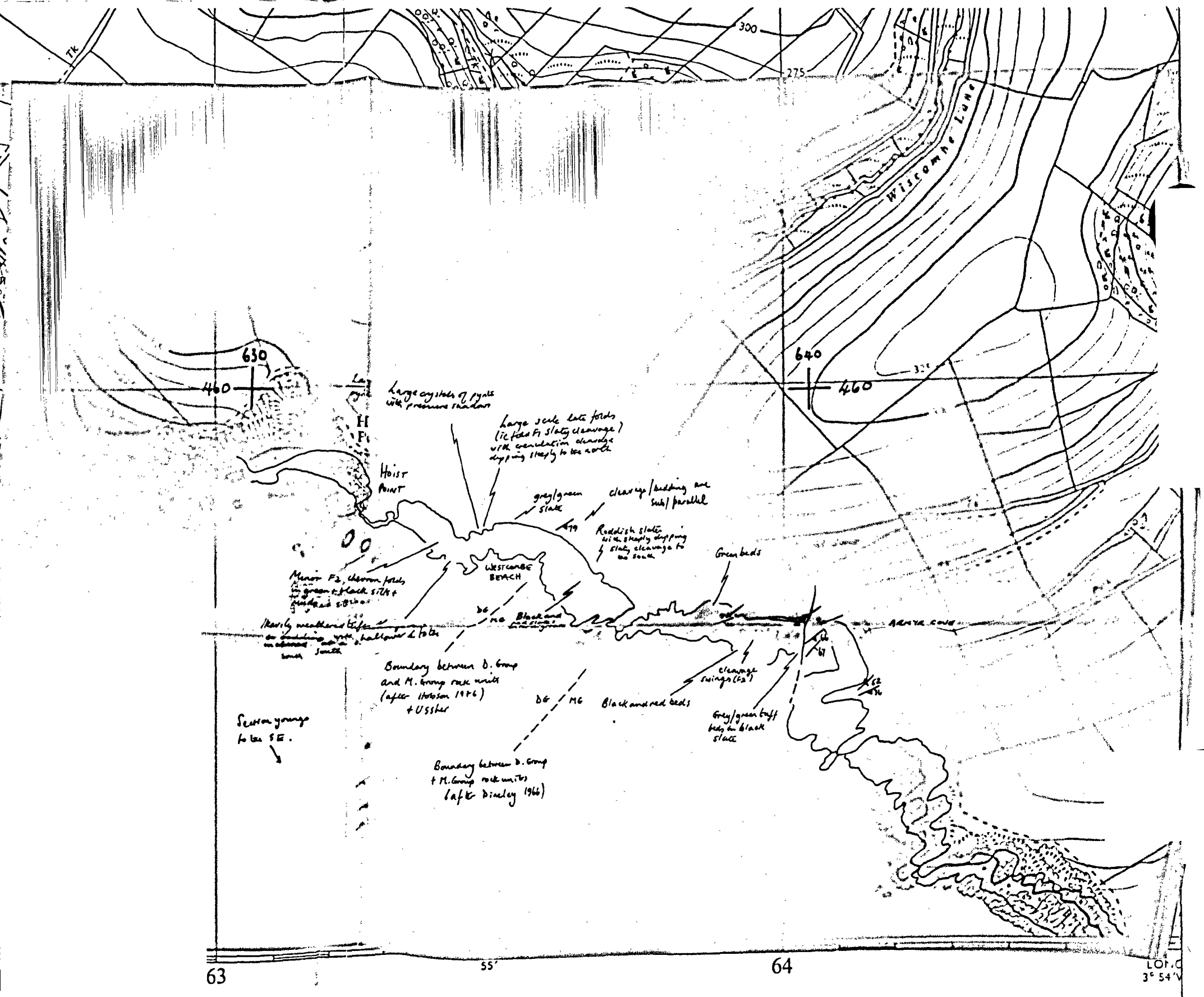
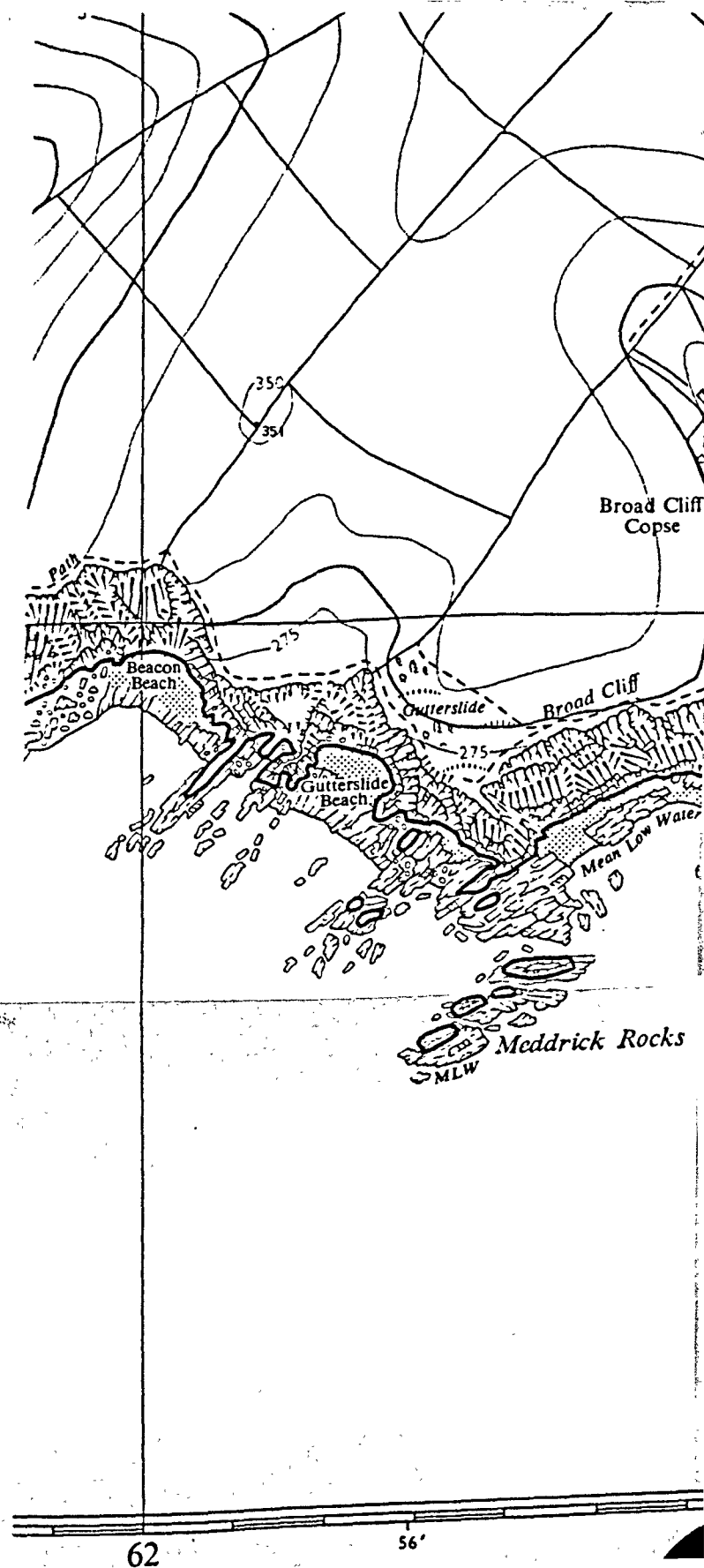
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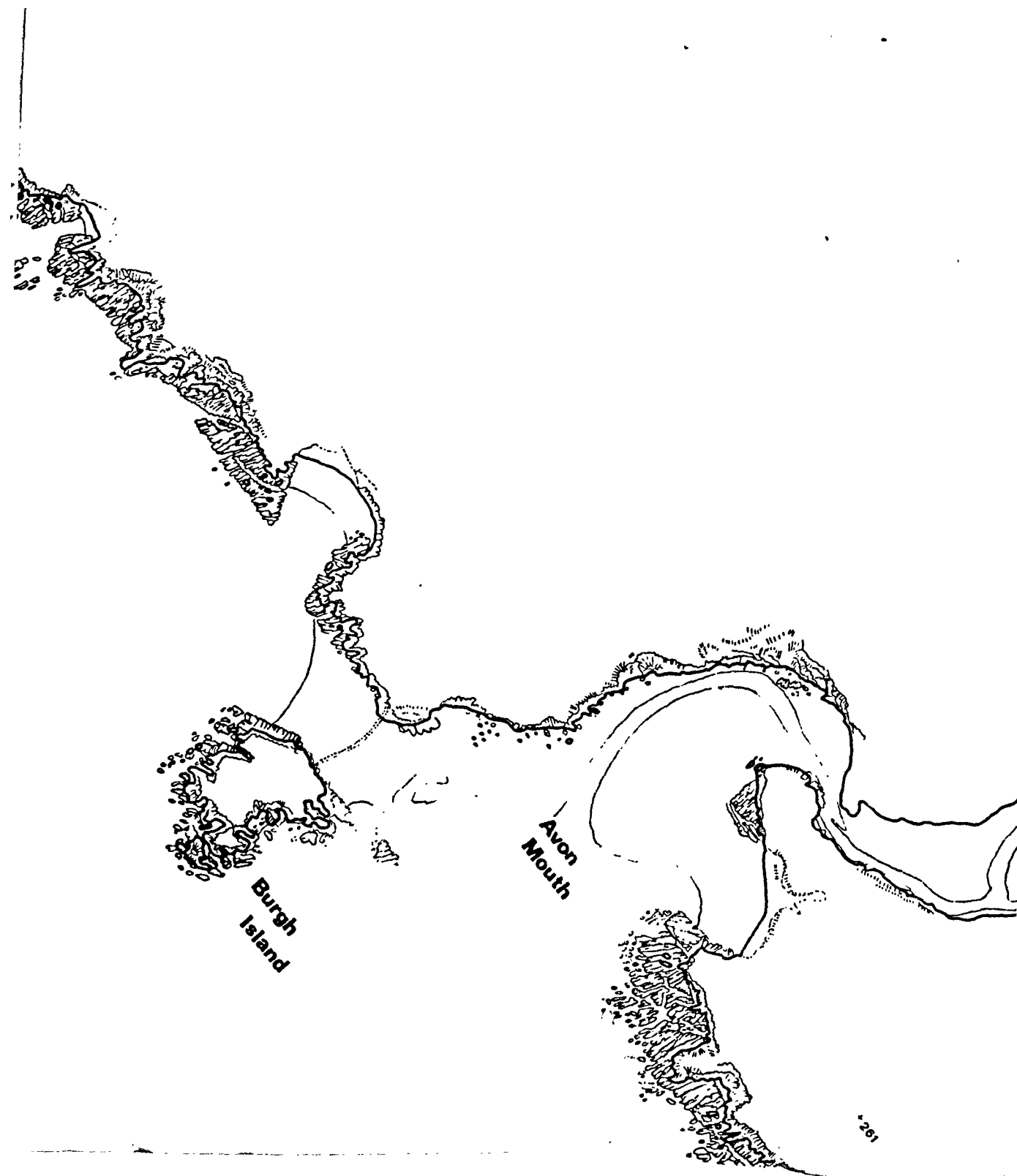


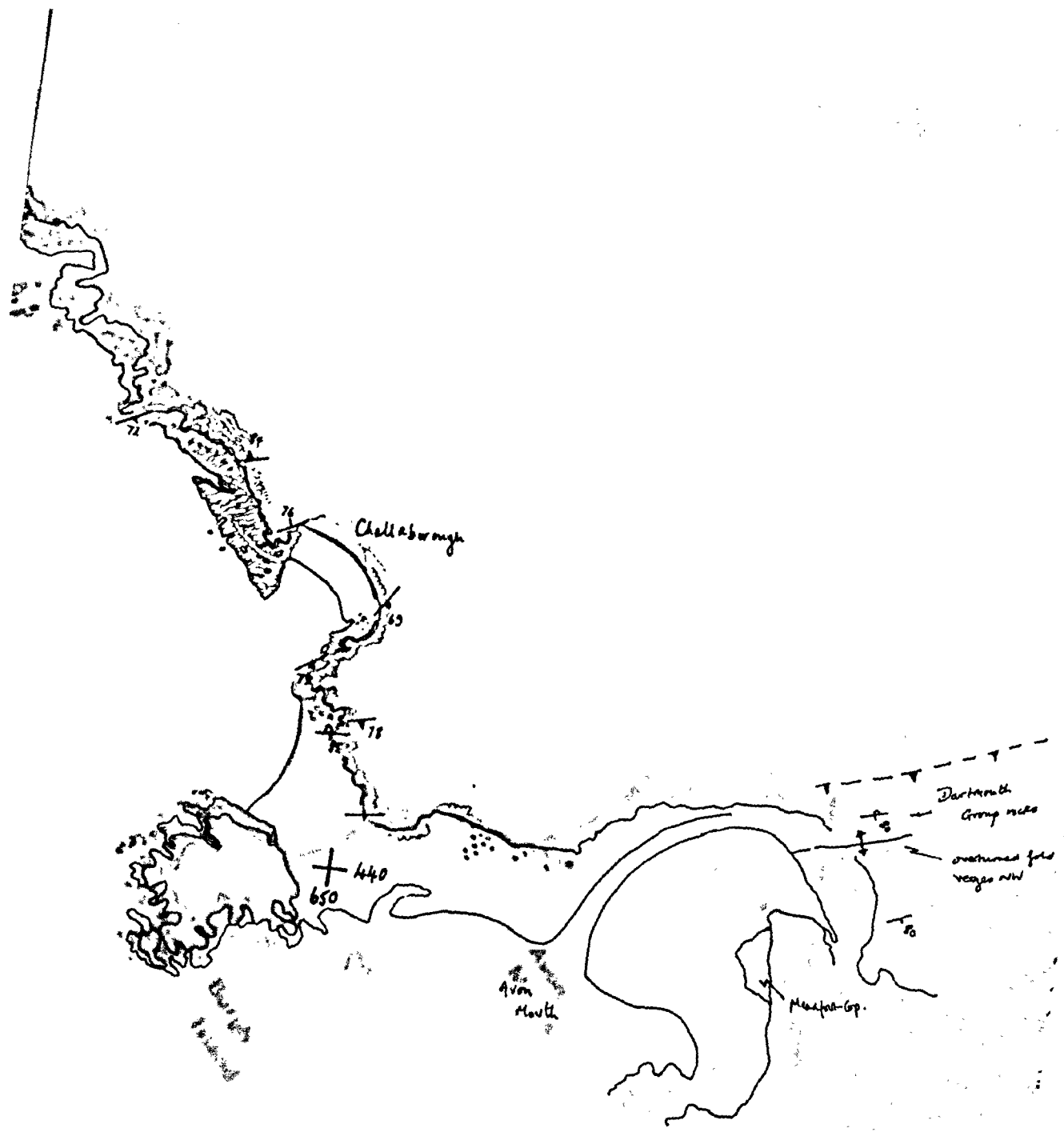
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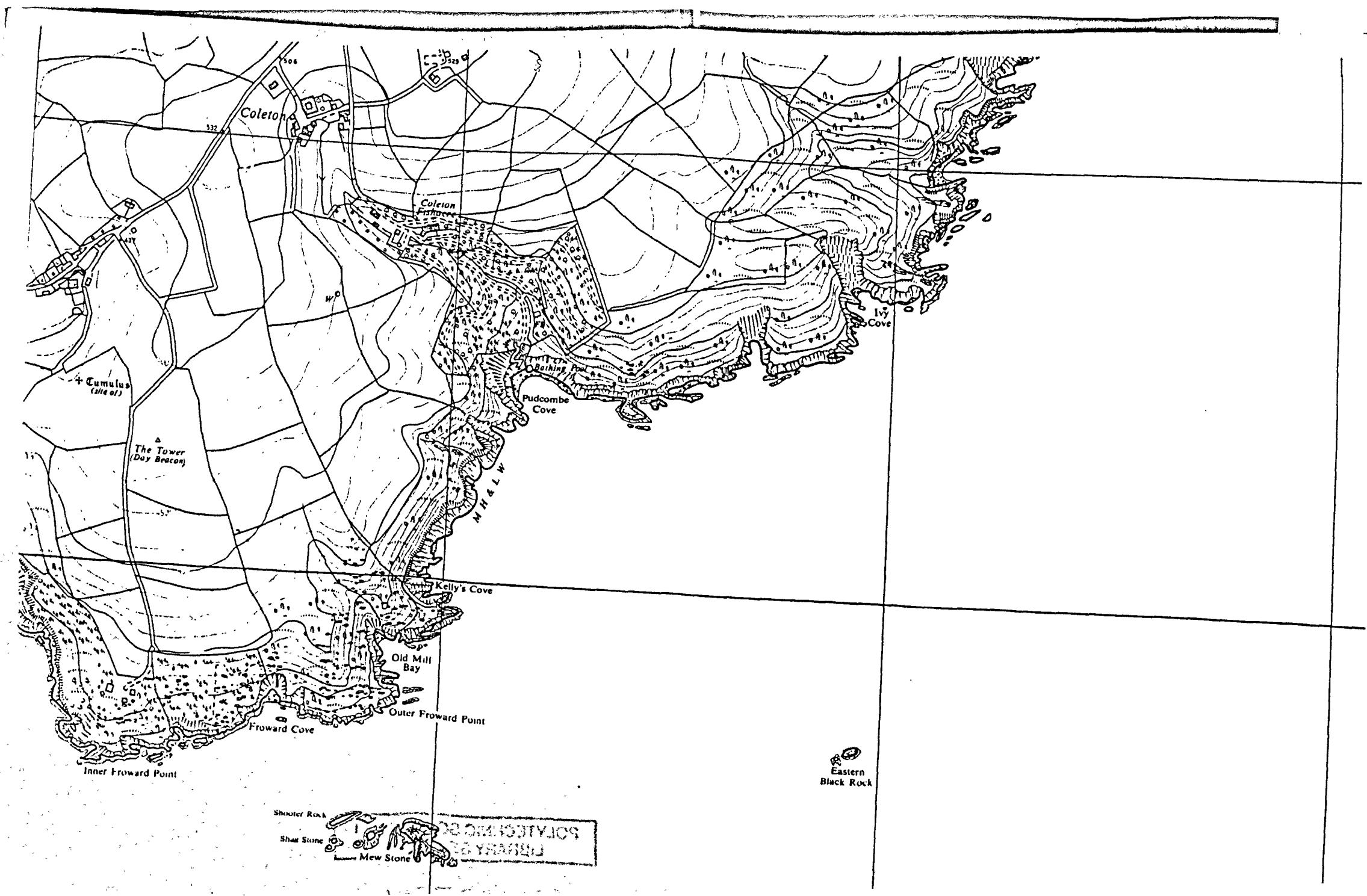


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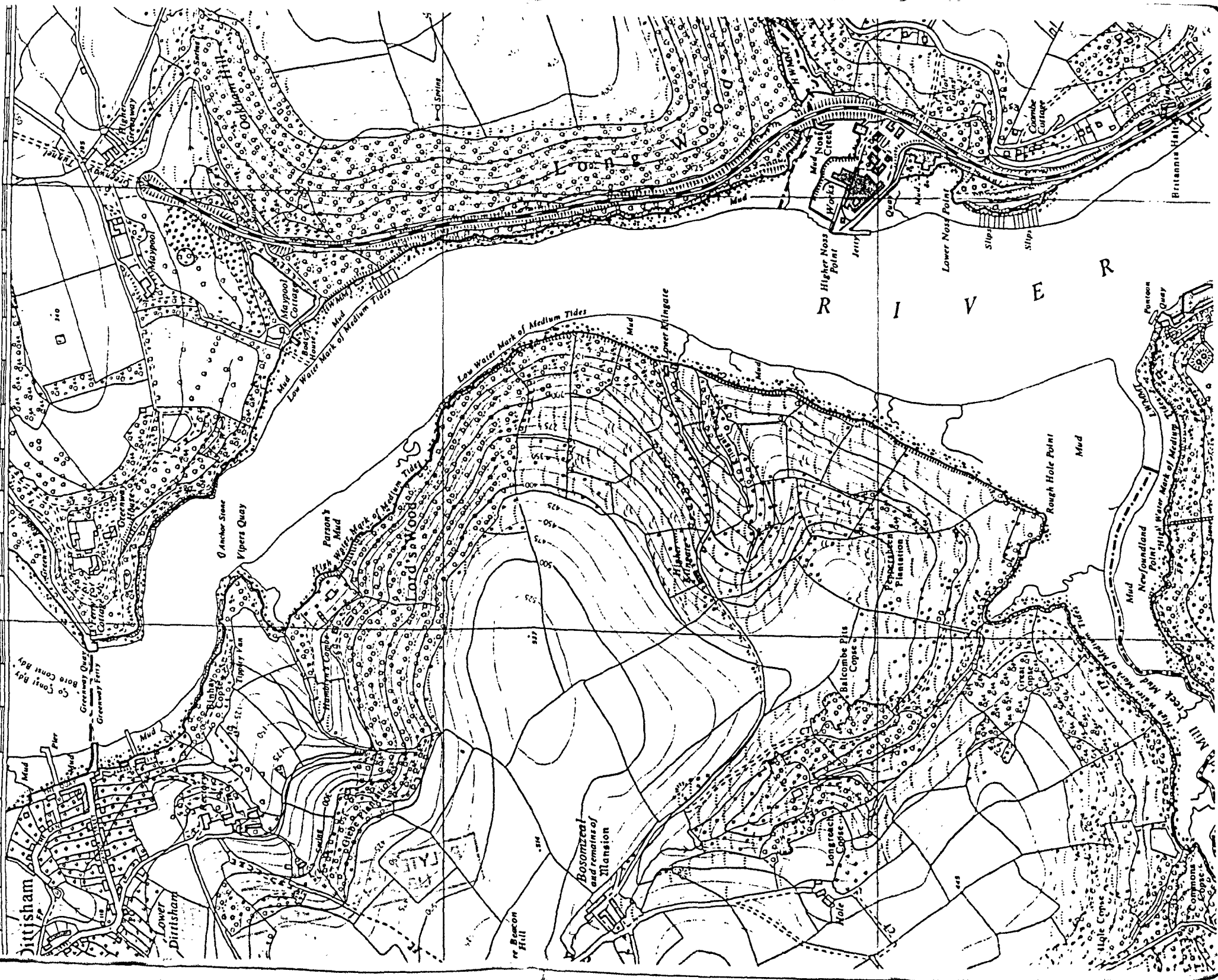
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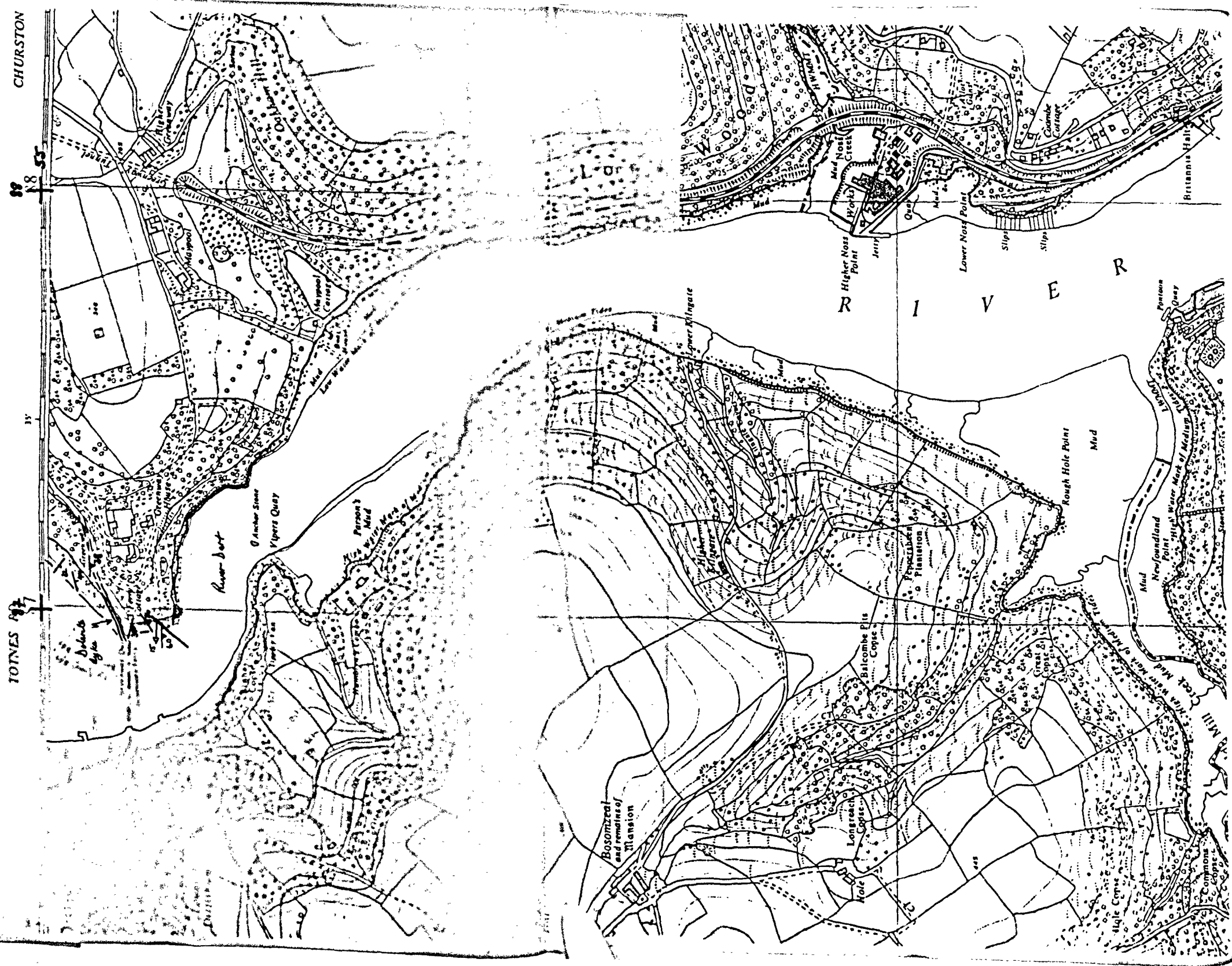
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CHURSTON

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CHURSTON

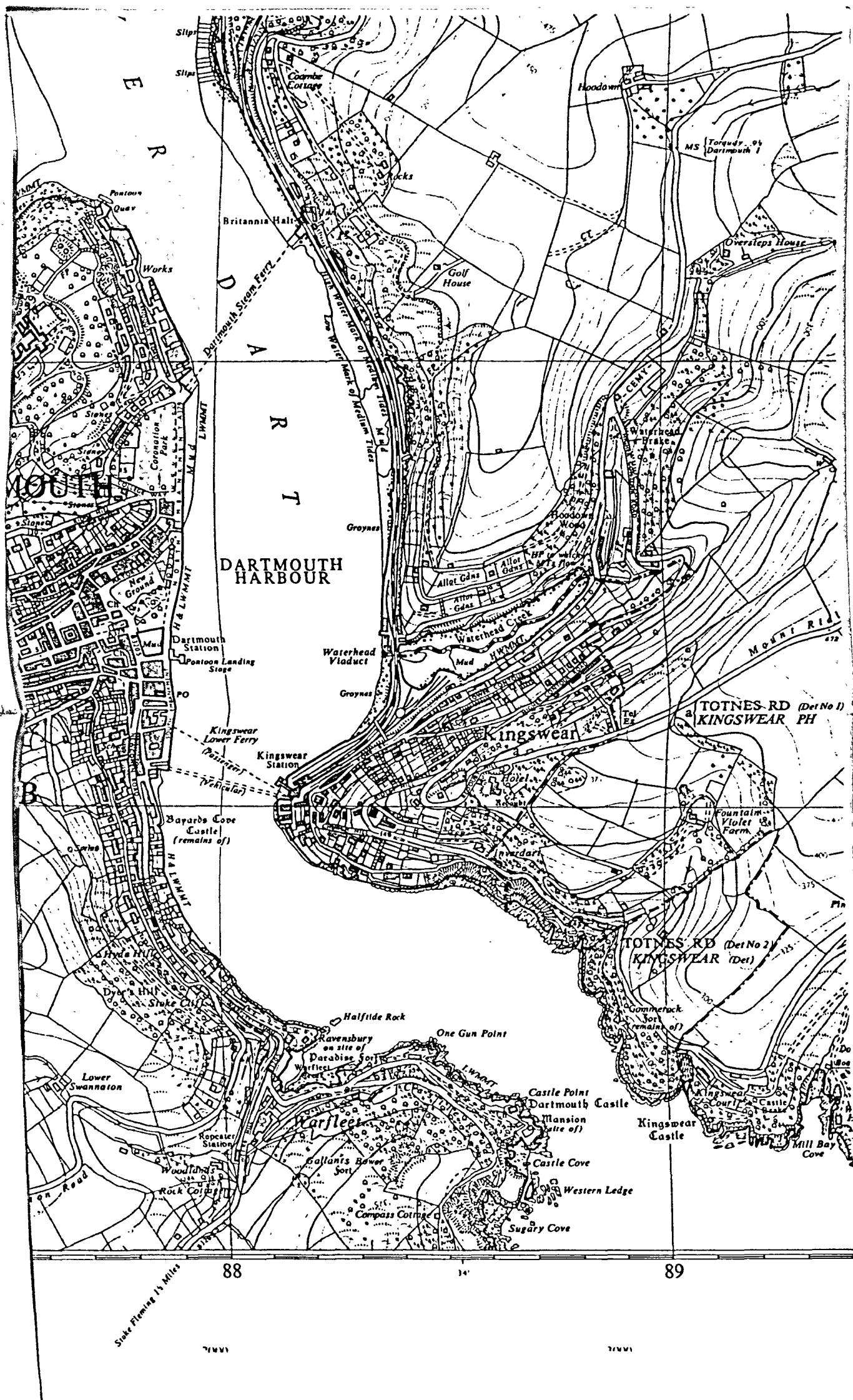


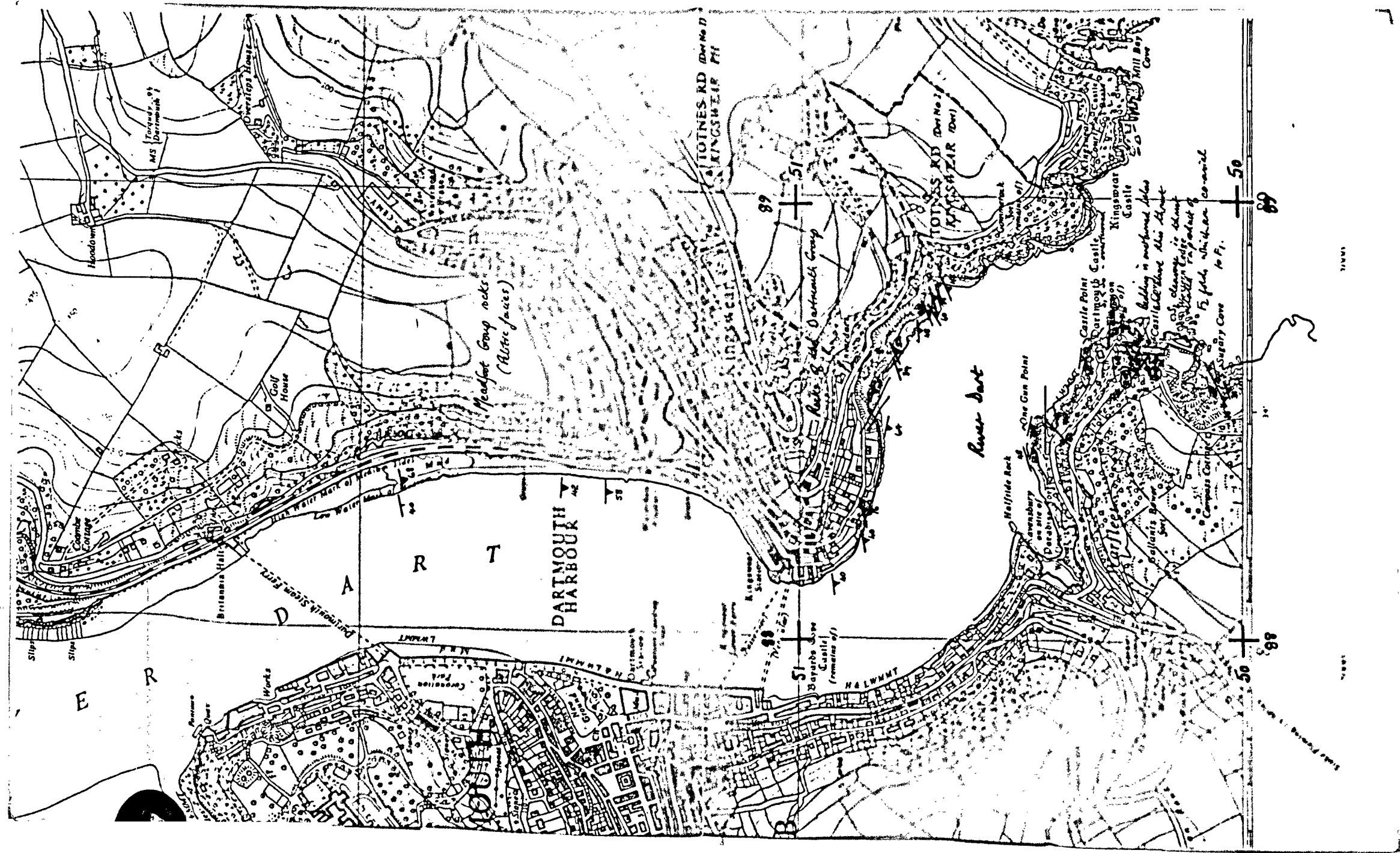
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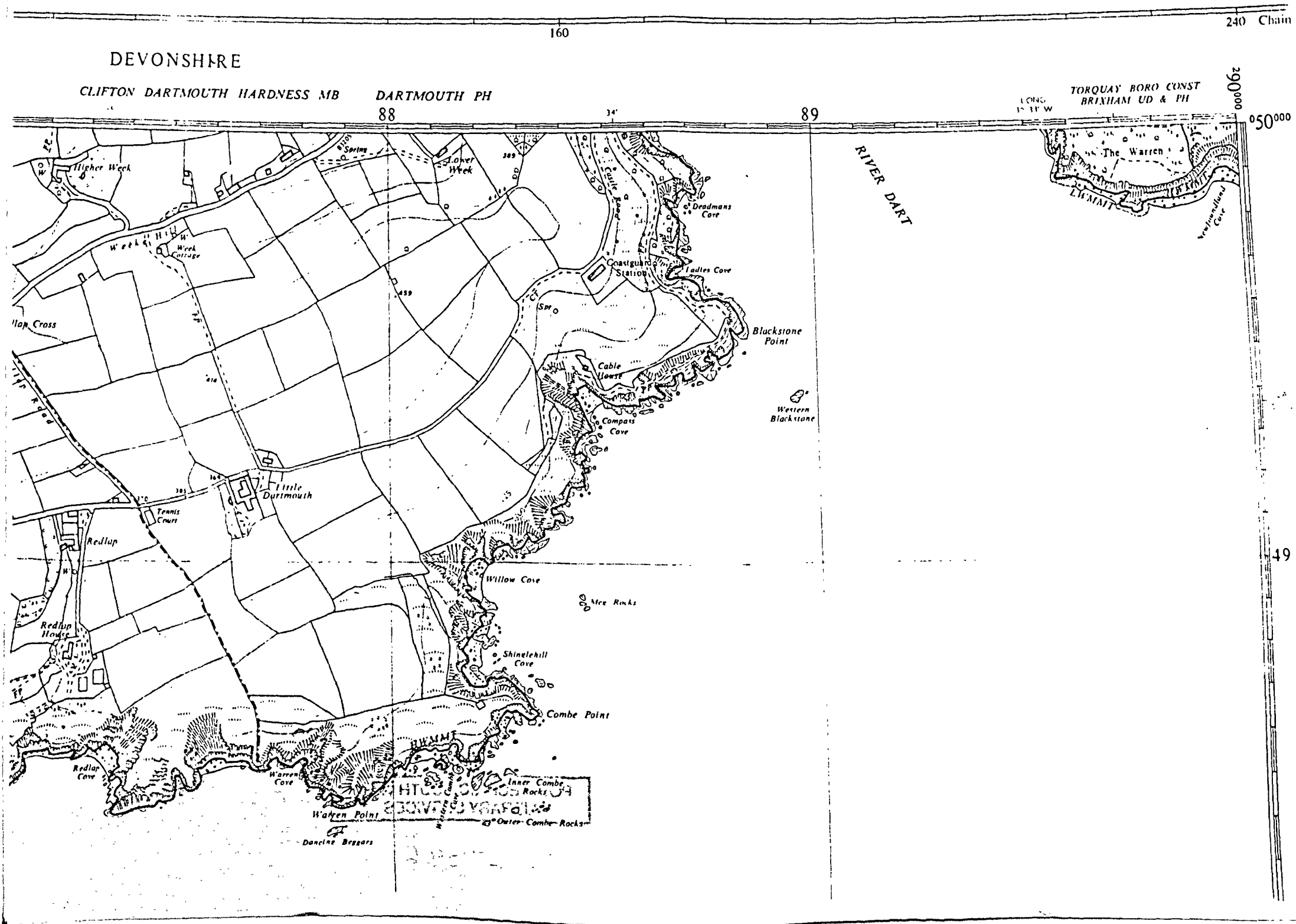
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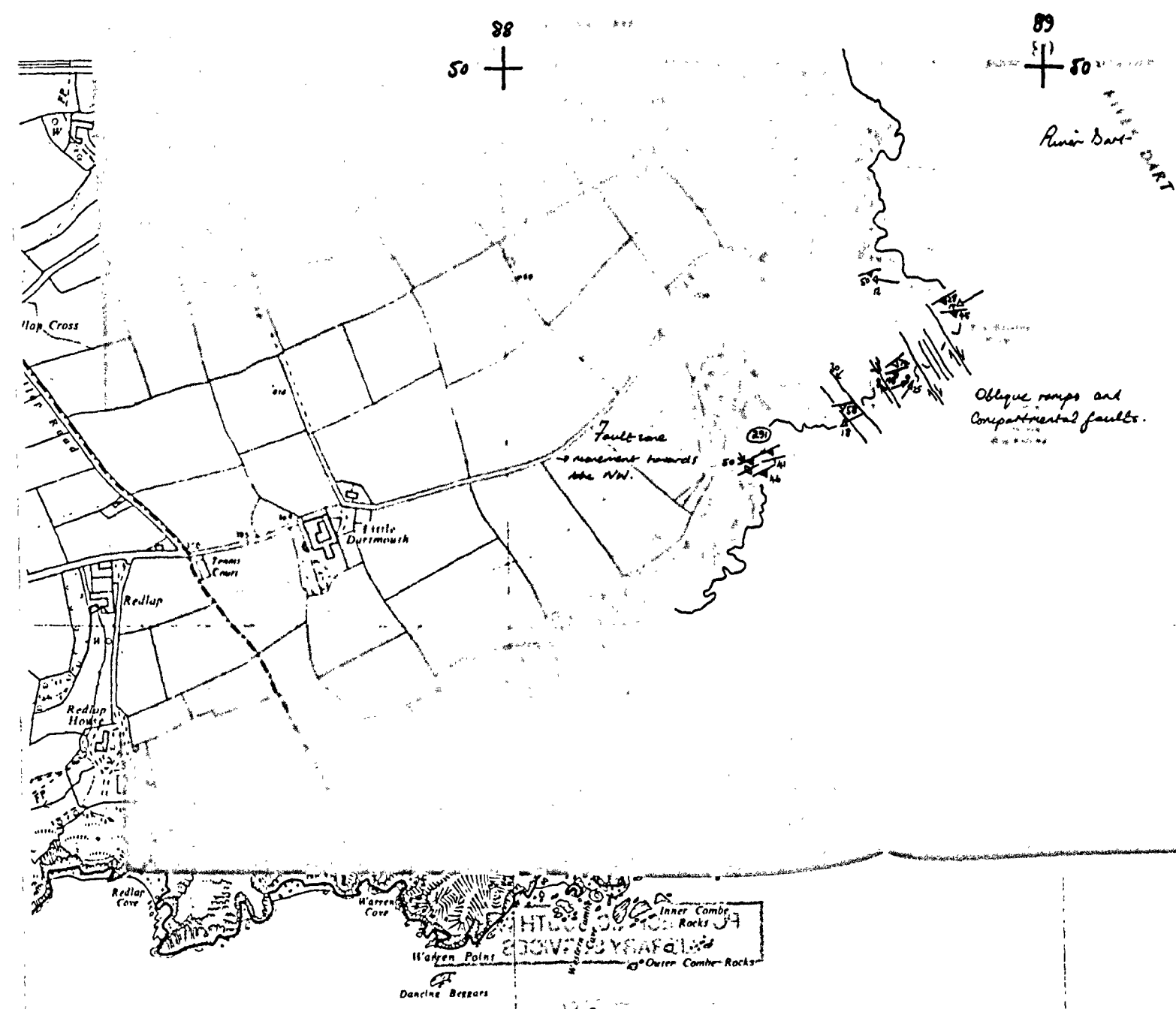
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Scale 1:10,000 or 6 inches to 1 mile

Sheet SA 04



Scale 1:10,500 or 6 inches to 1 mile



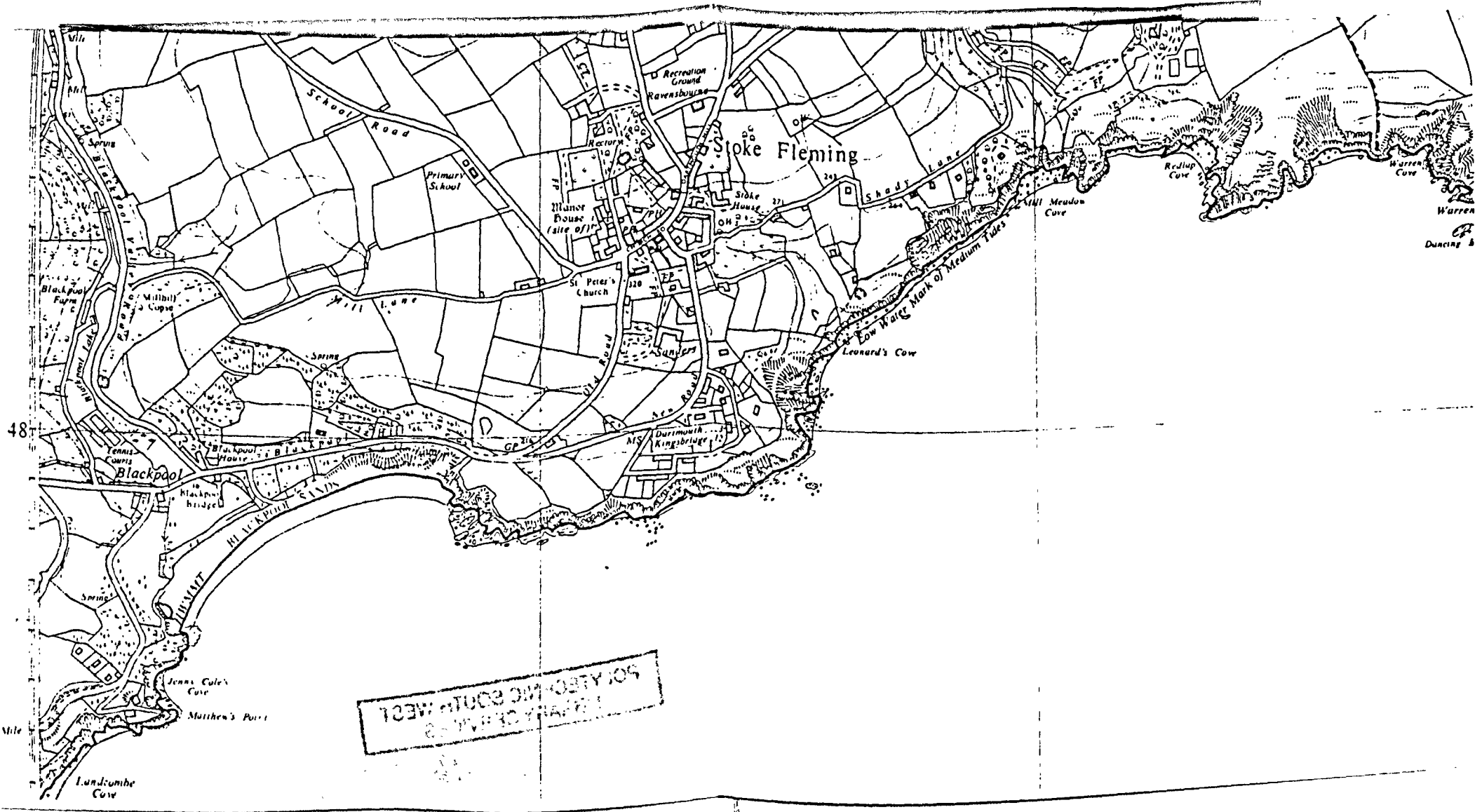
APPENDIX 3

XXVIII

POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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KINGSBRIDGE RI

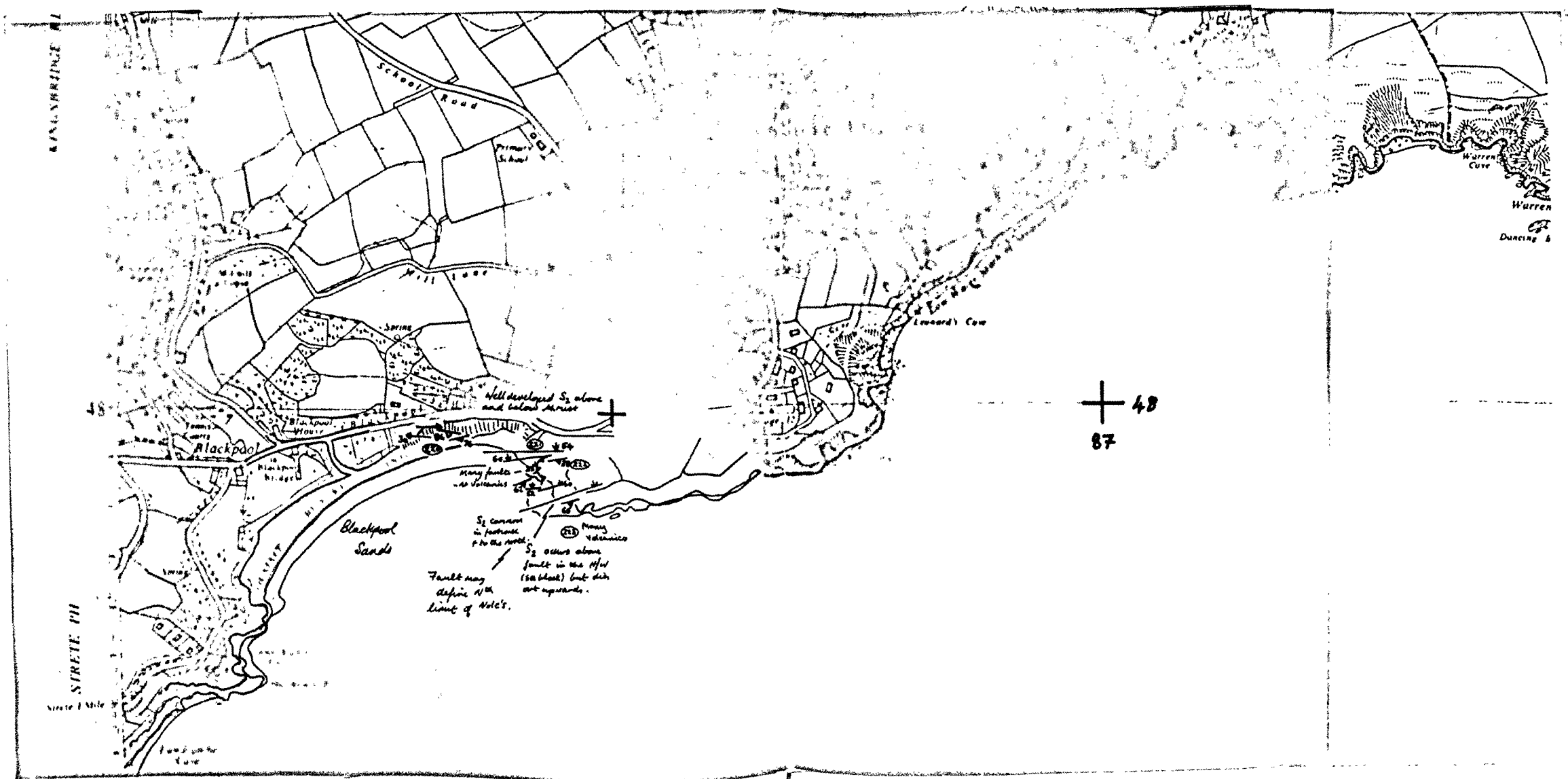


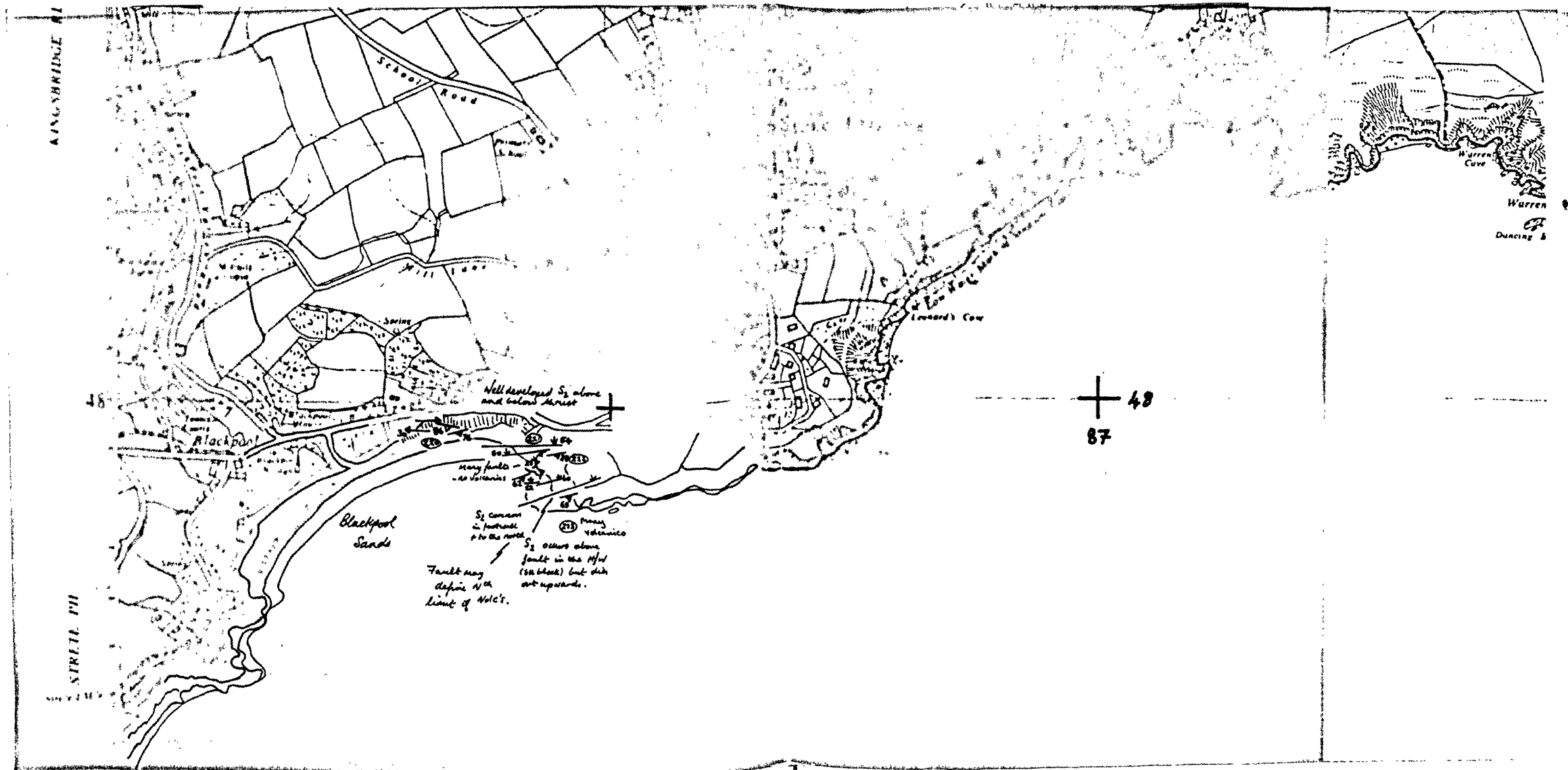
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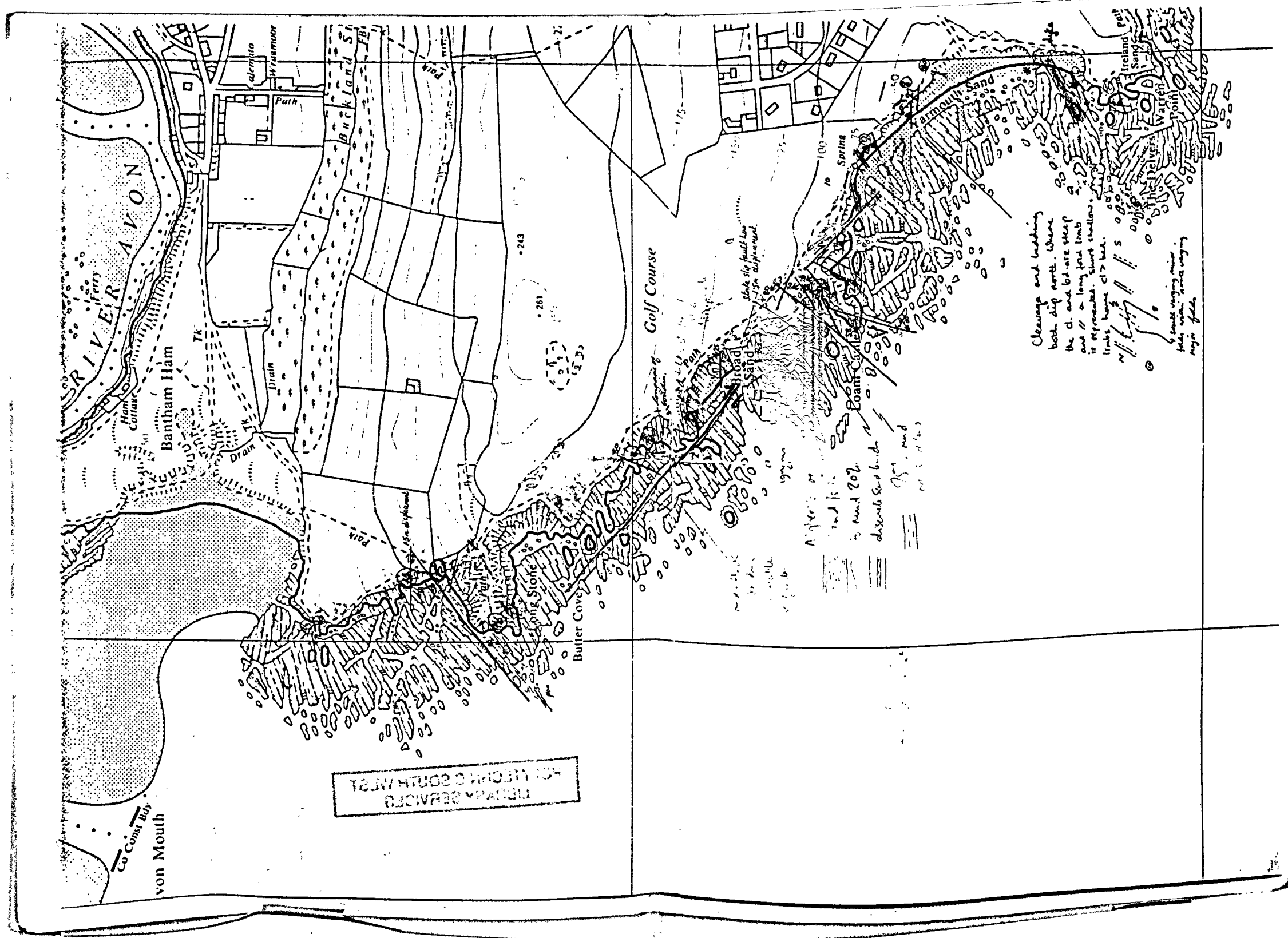
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About 1 Mile

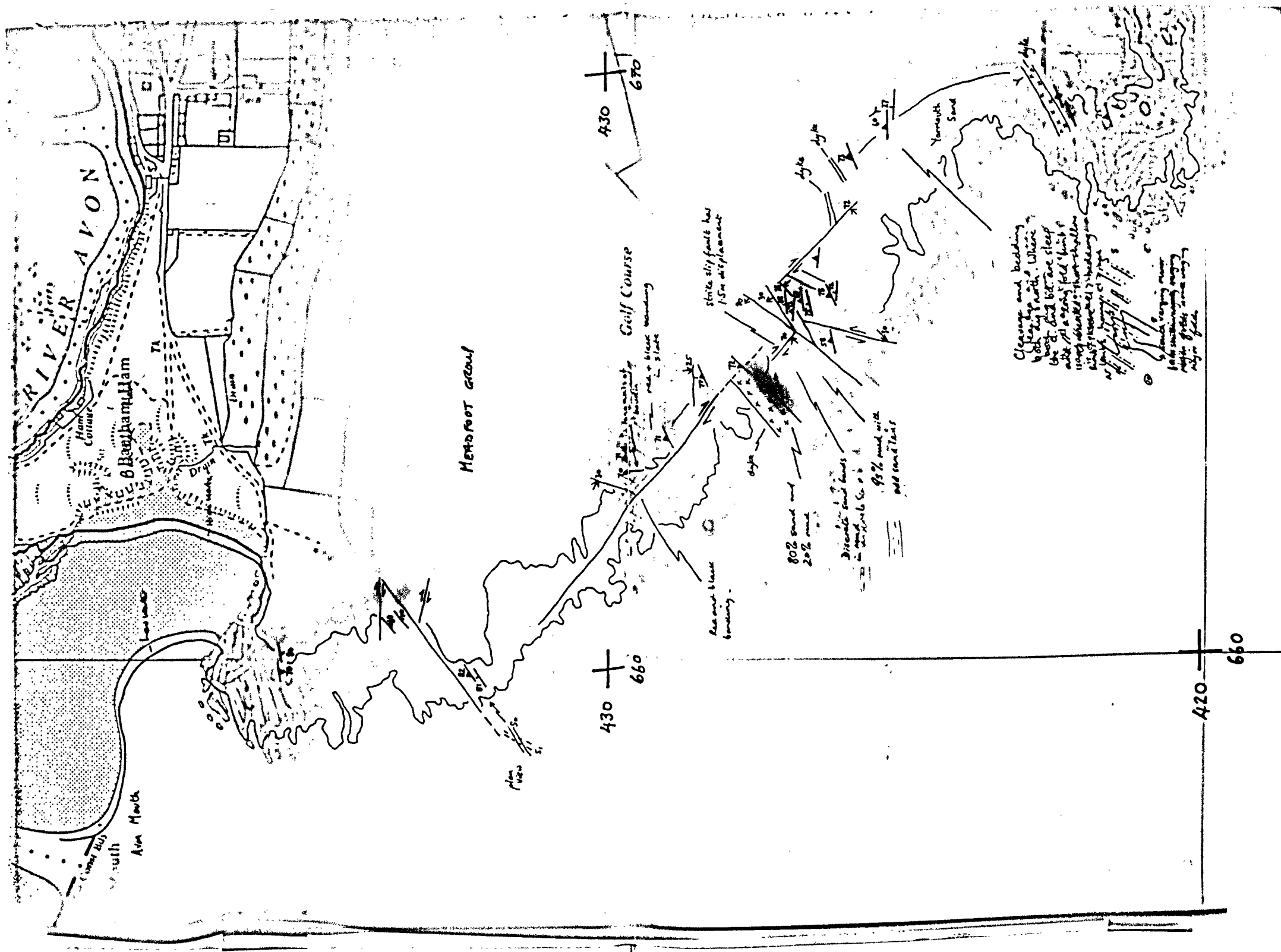
STRETE III
About 1 Mile

Warren
Dancing &







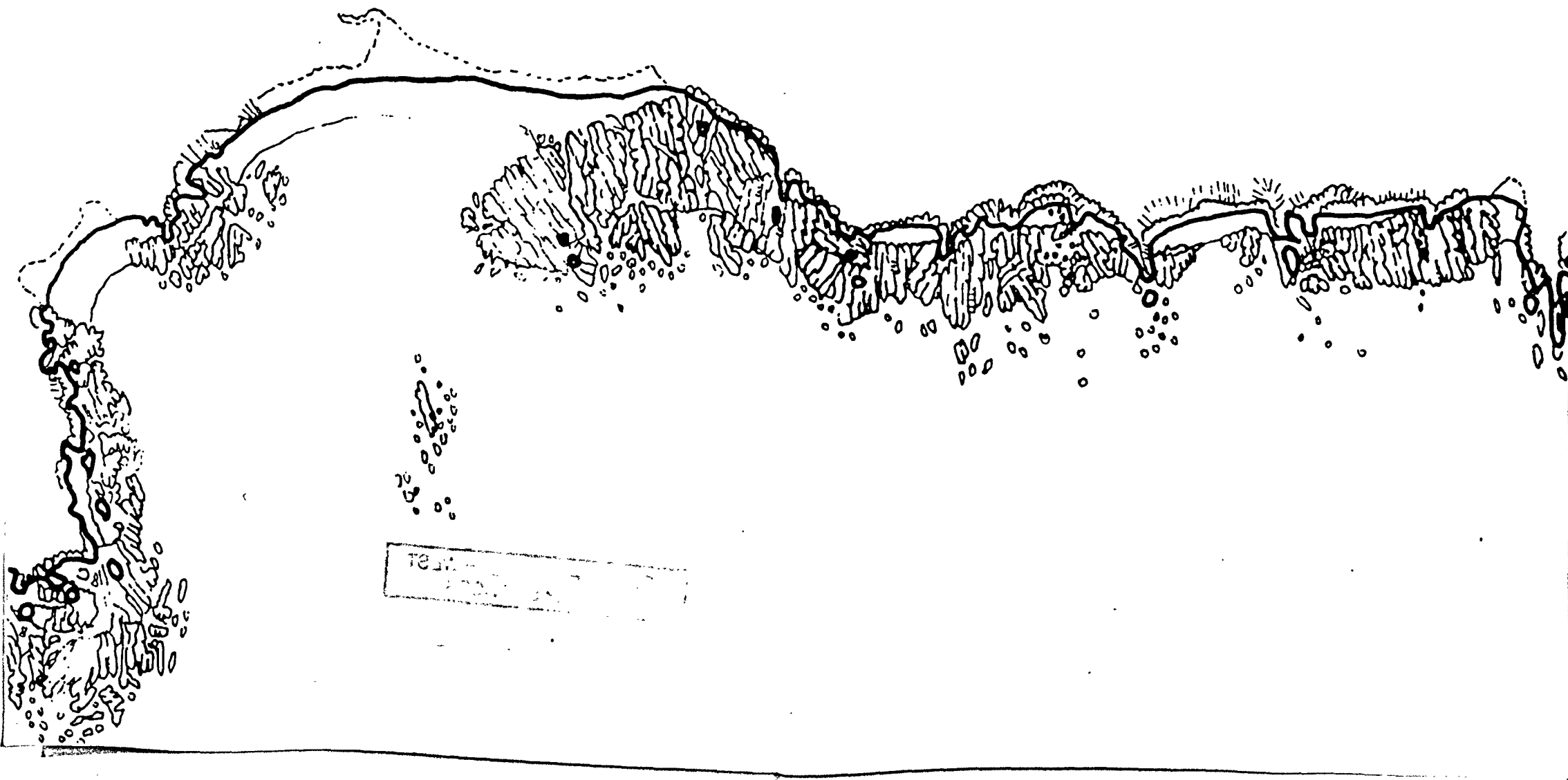


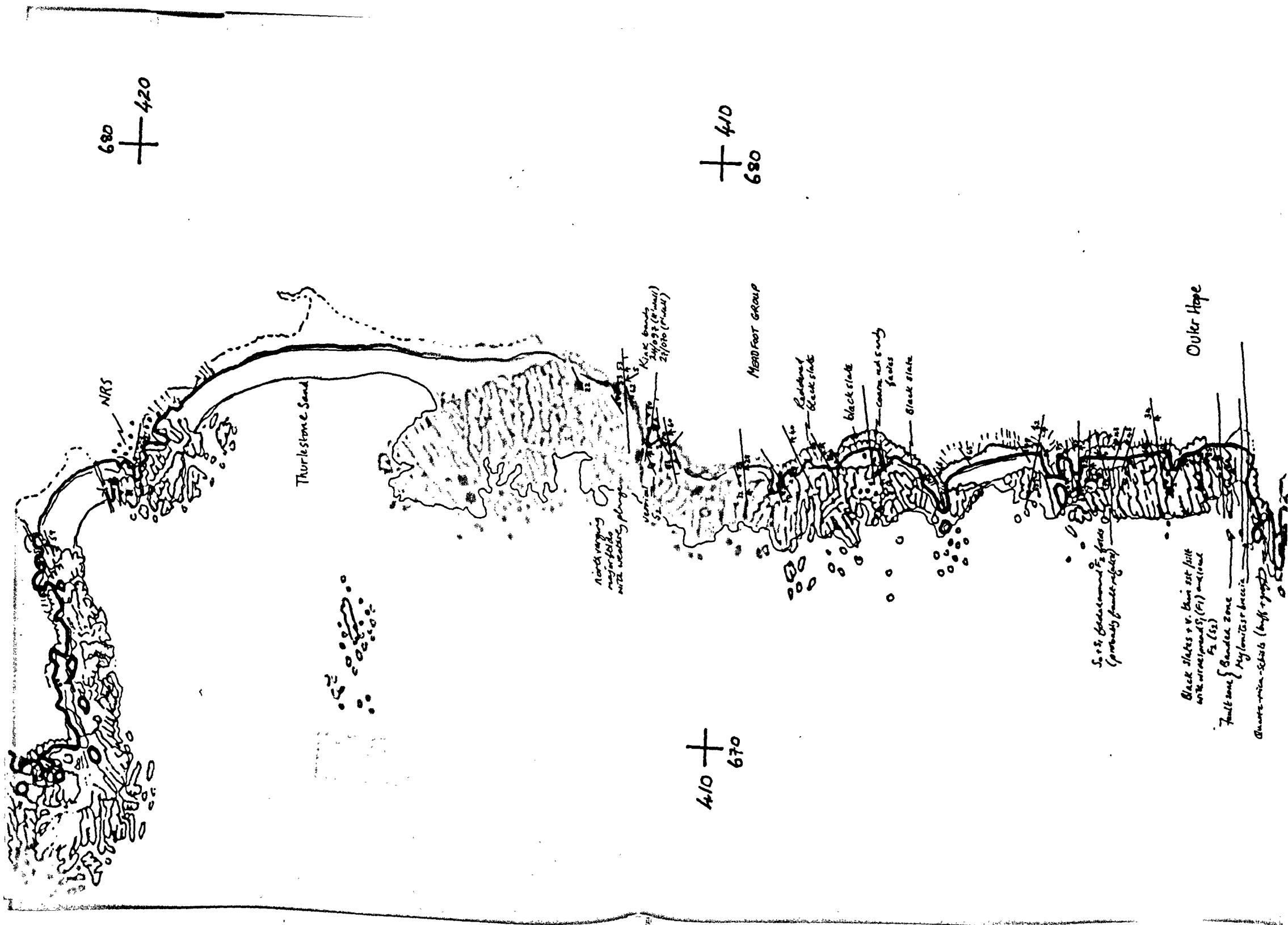
APPENDIX 3

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POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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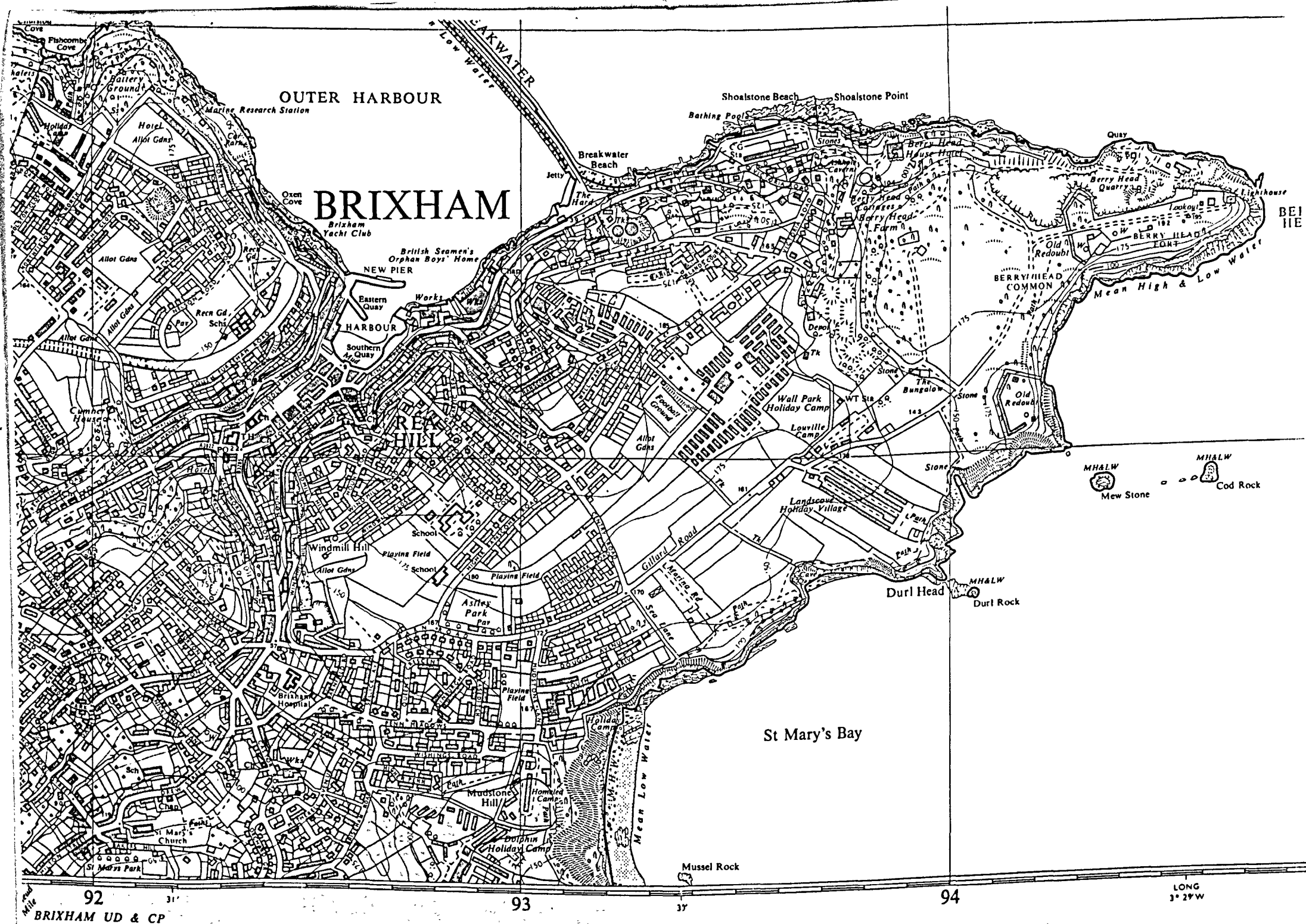


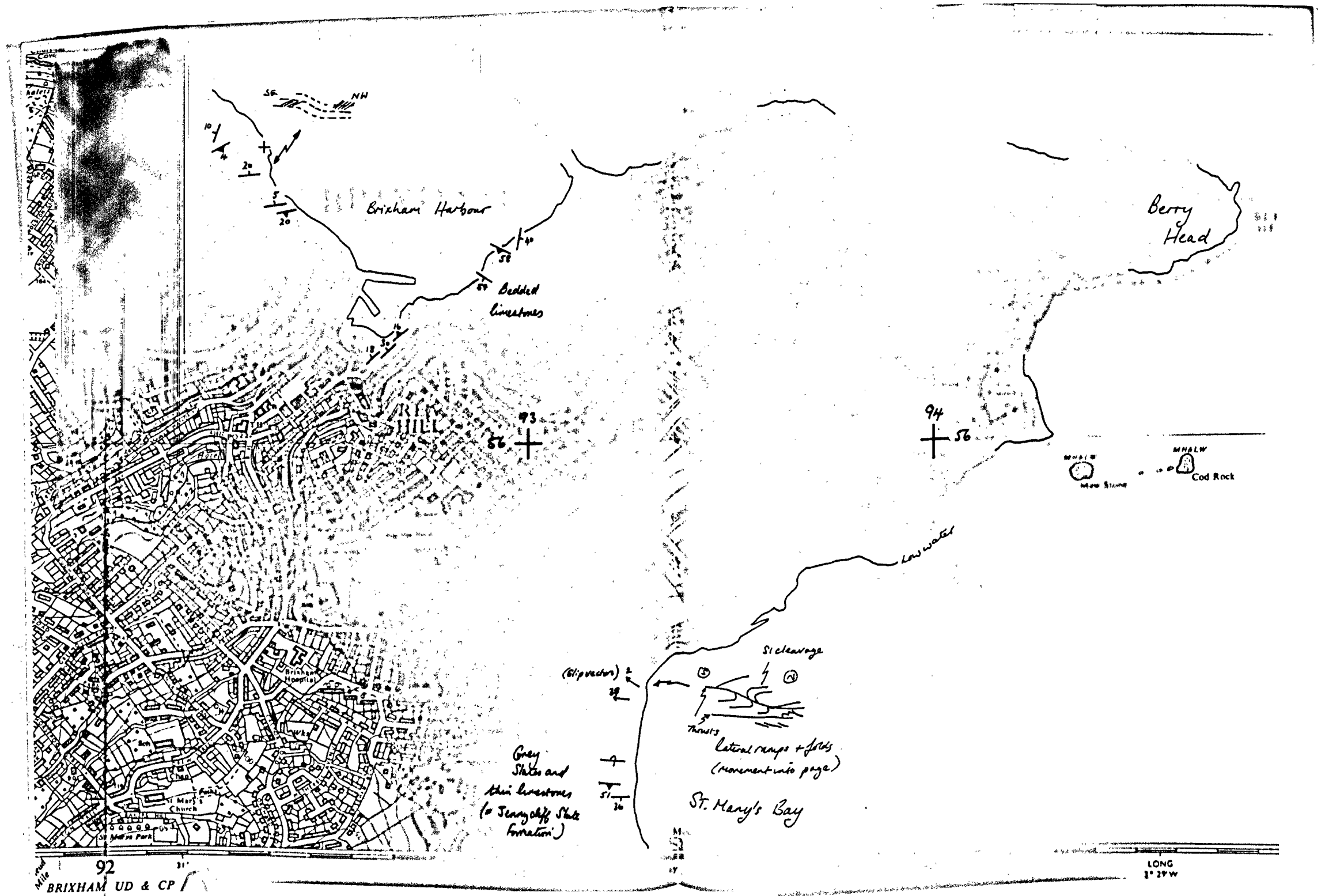
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XXI

POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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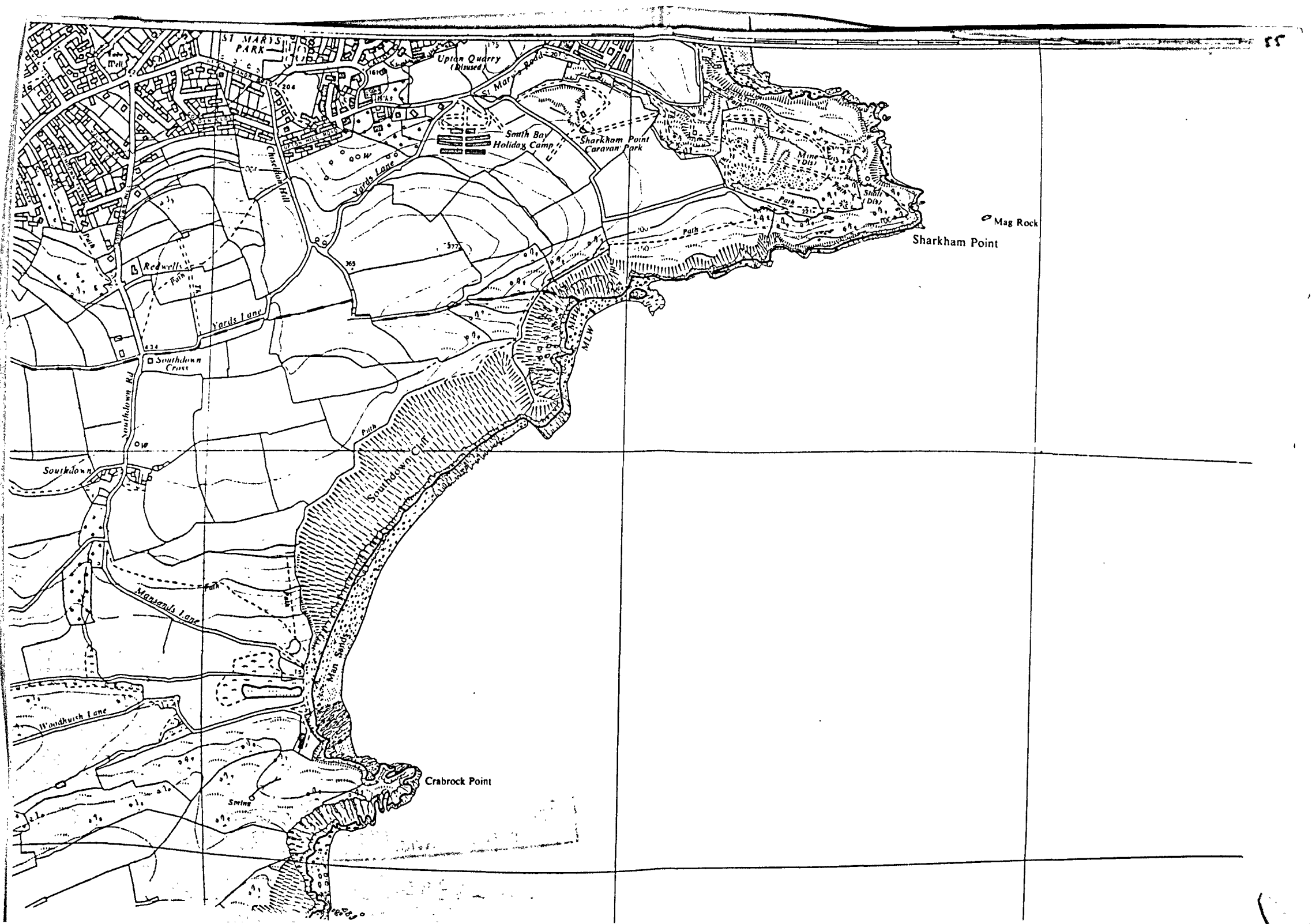


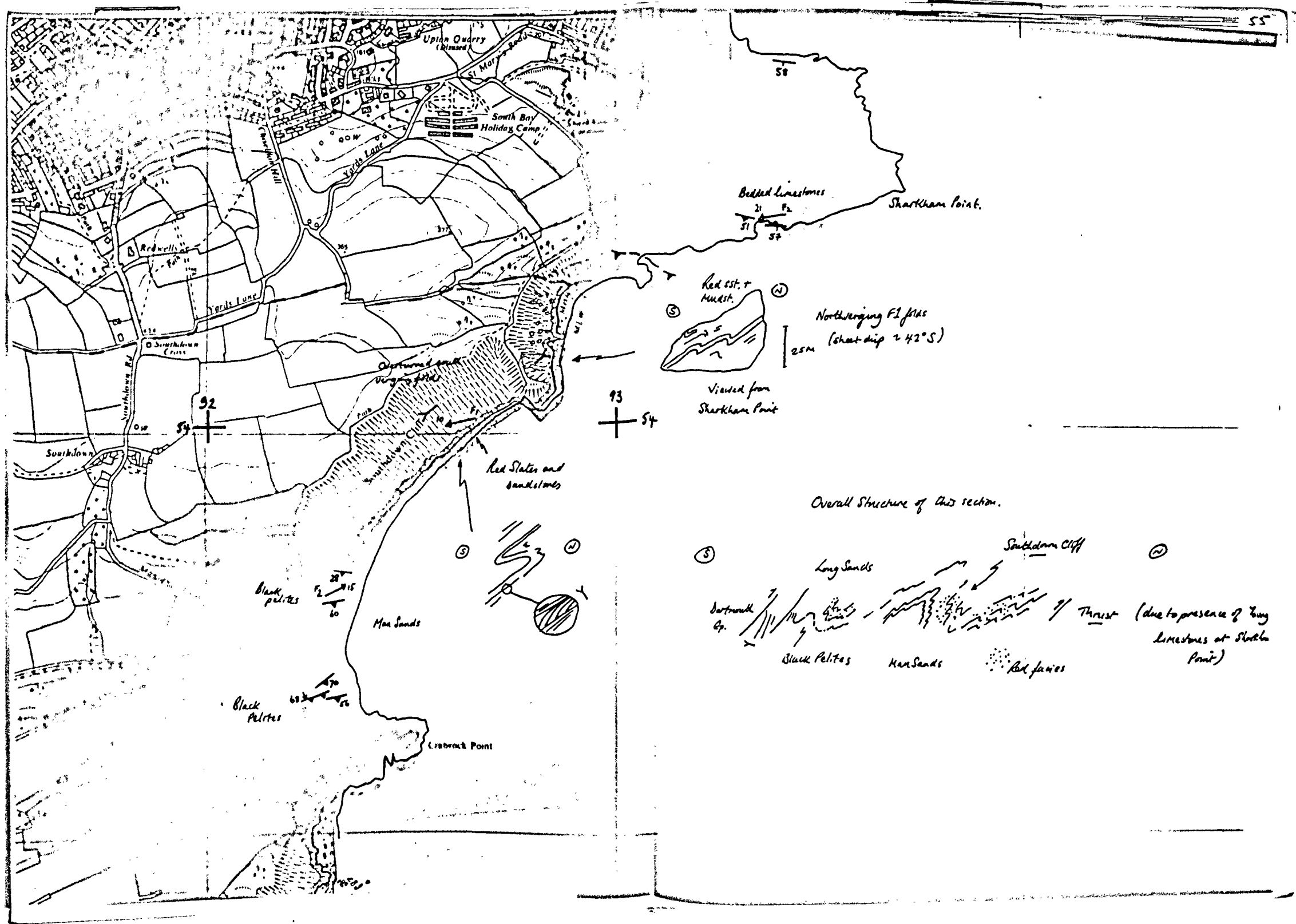
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LIBRARY SERVICE

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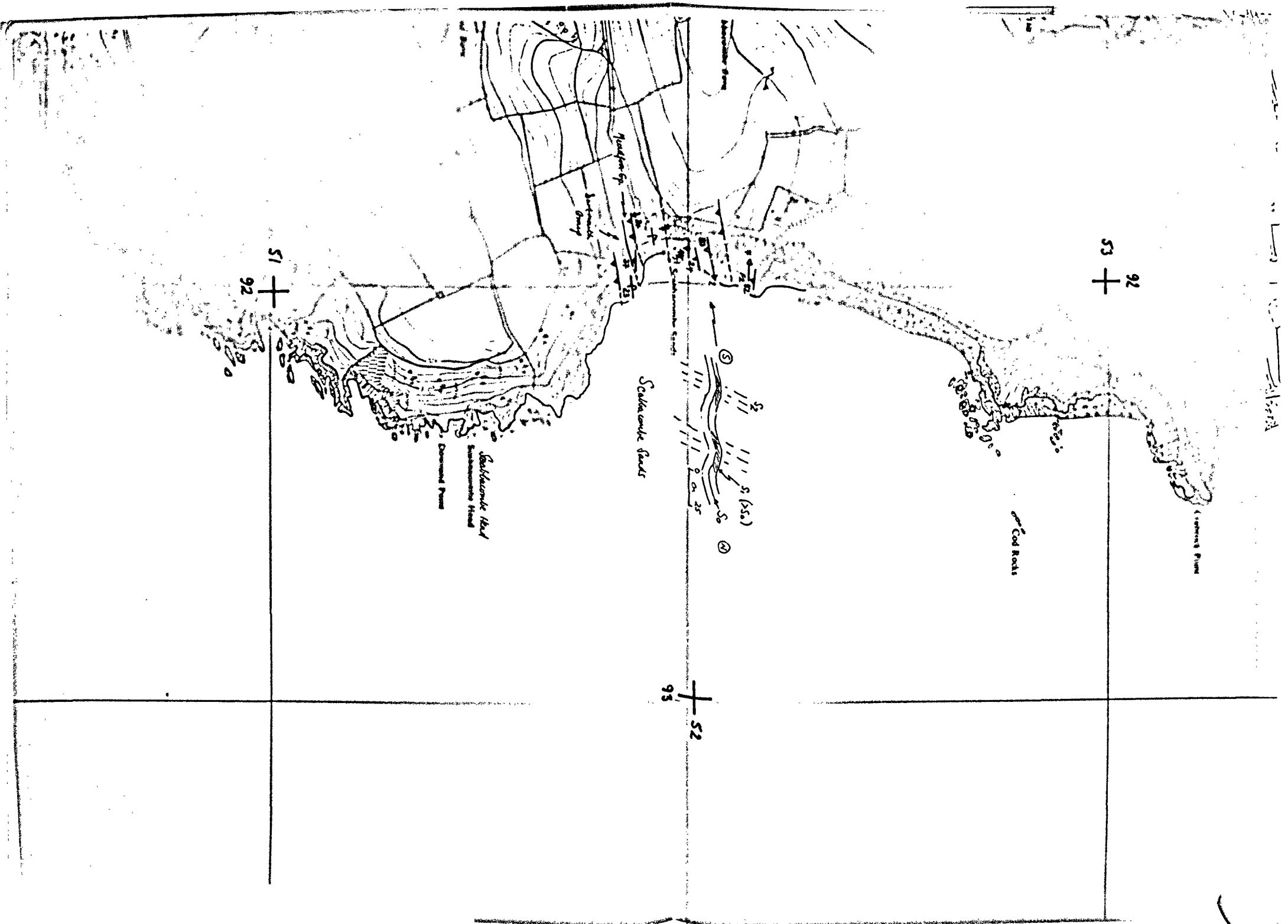
APPENDIX 3

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POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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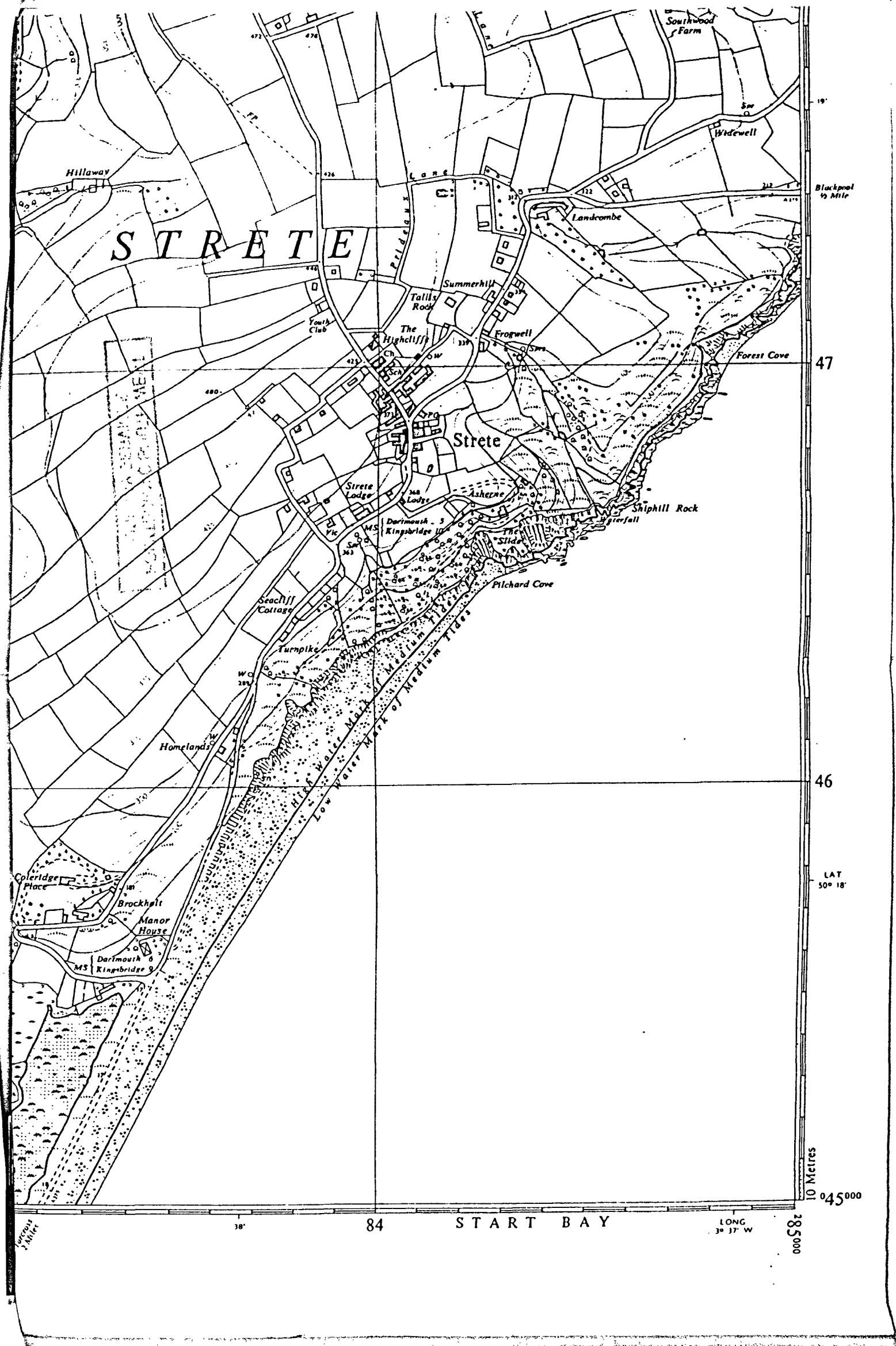


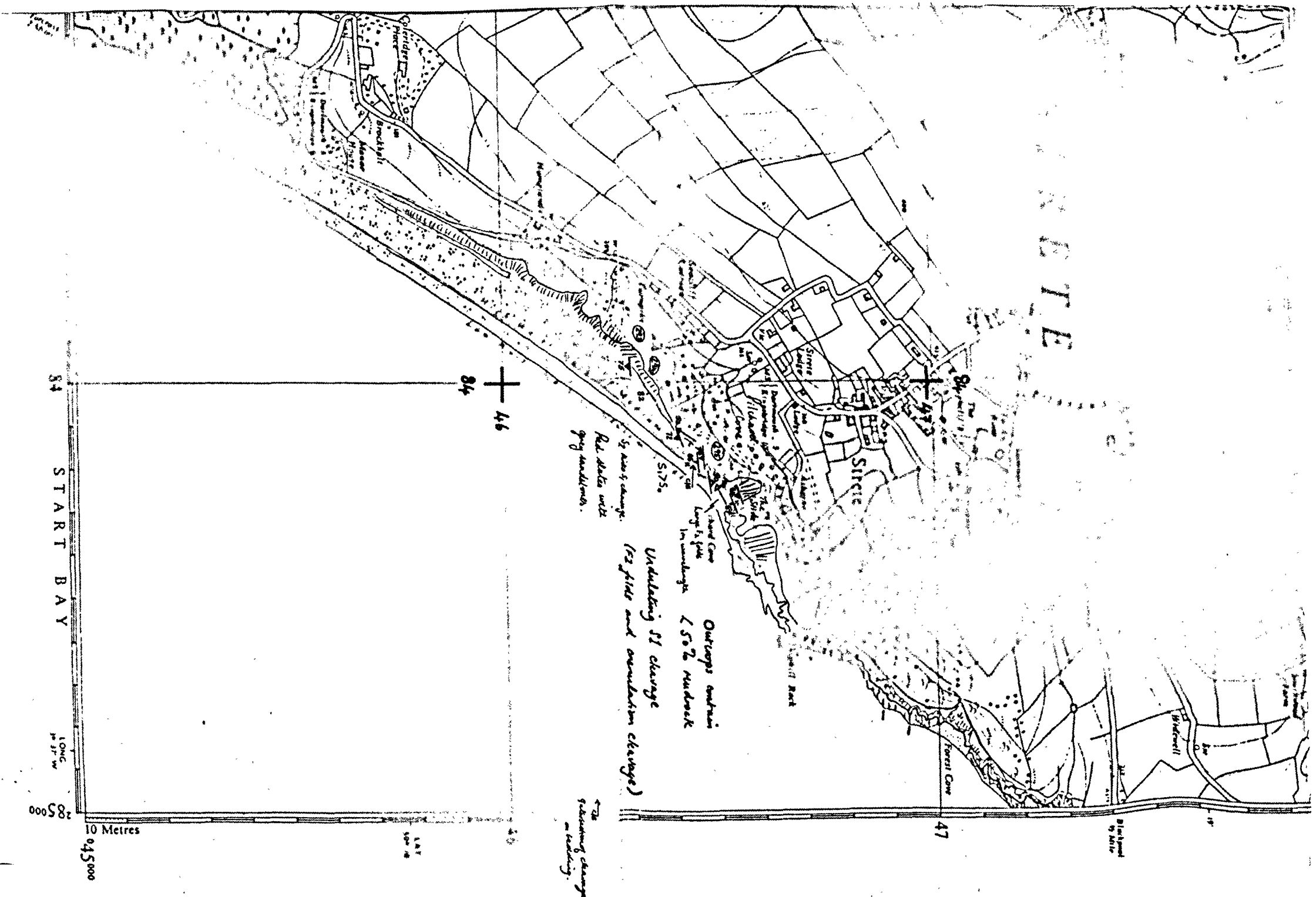
APPENDIX 3

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POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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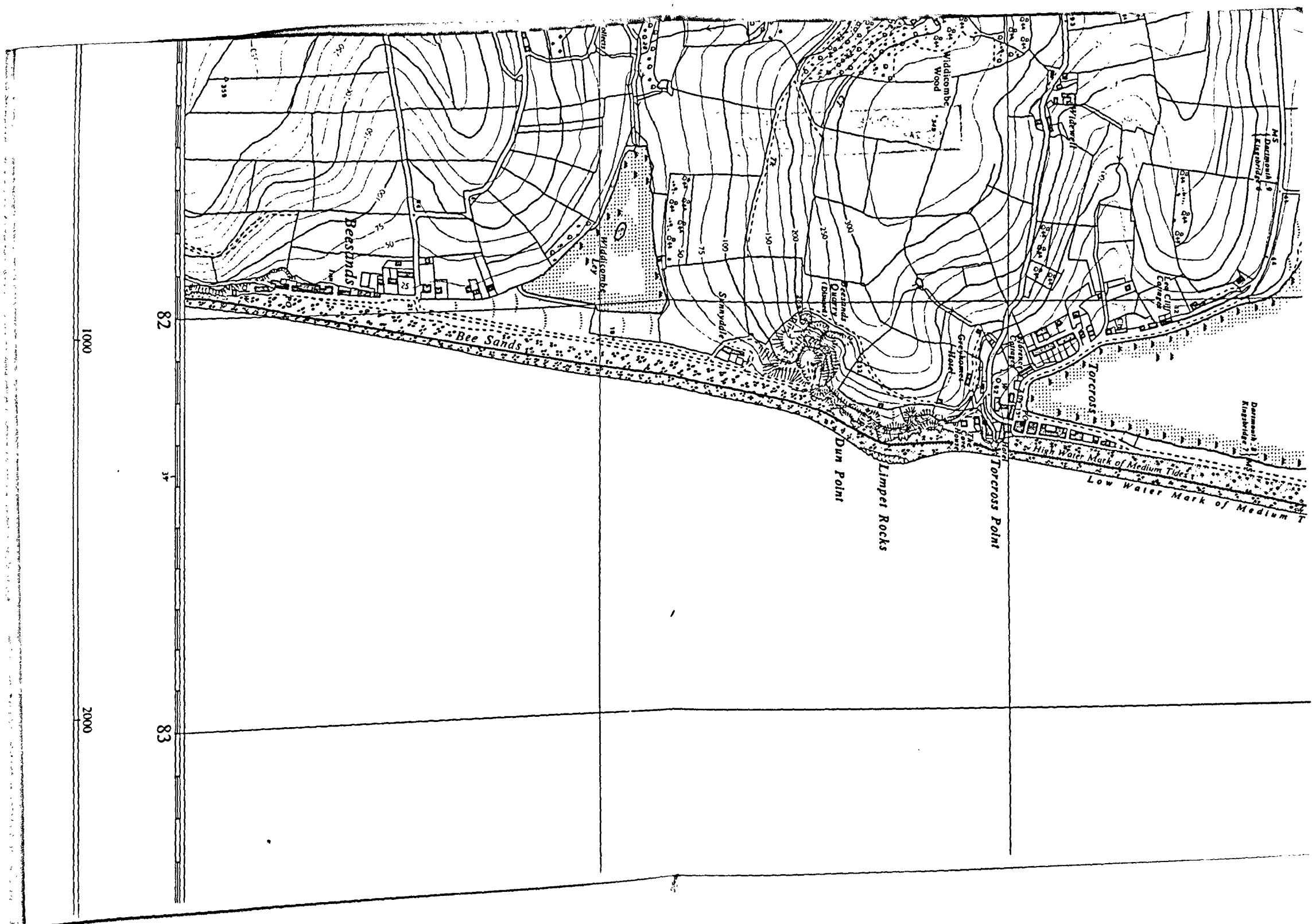


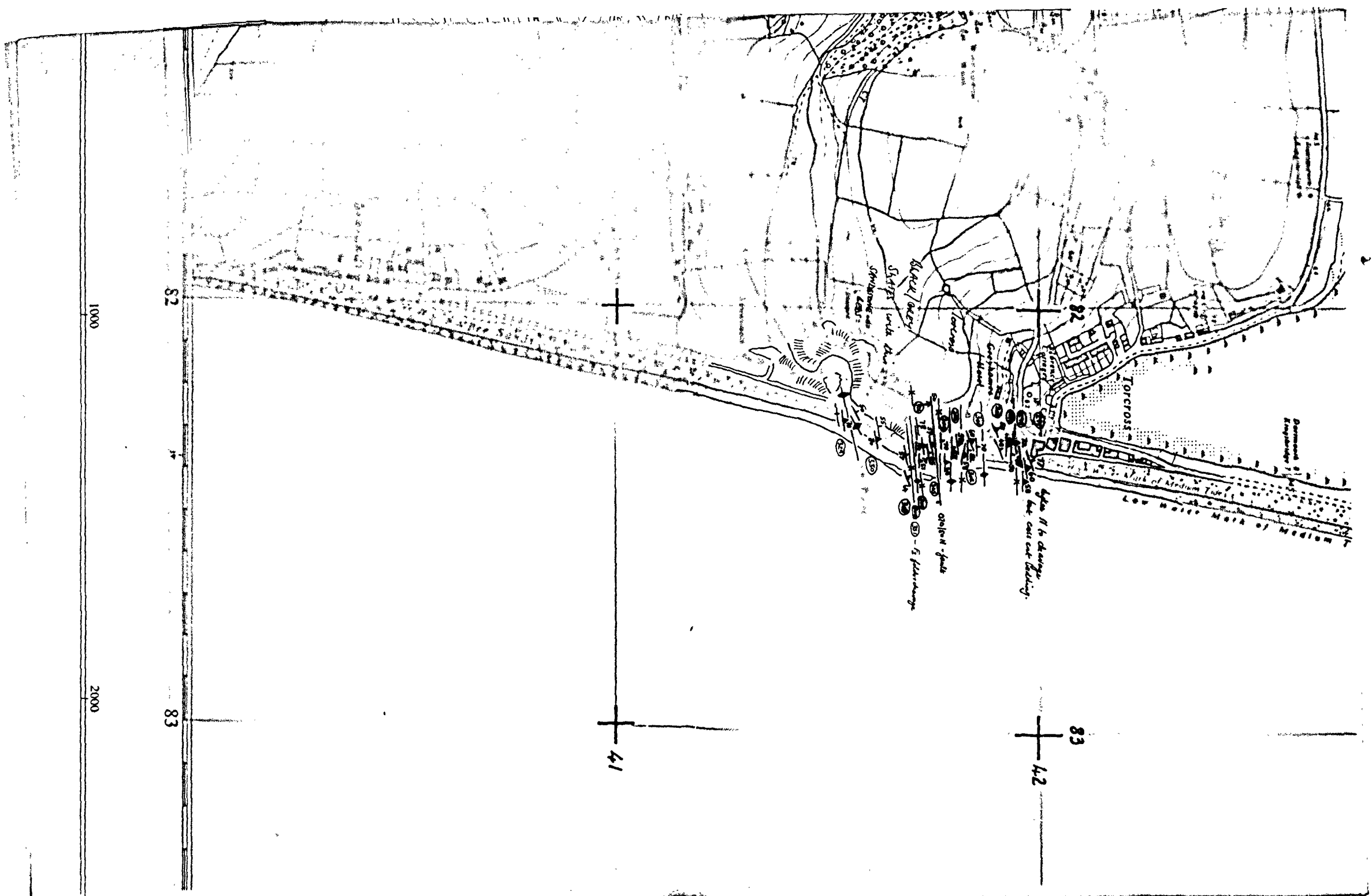
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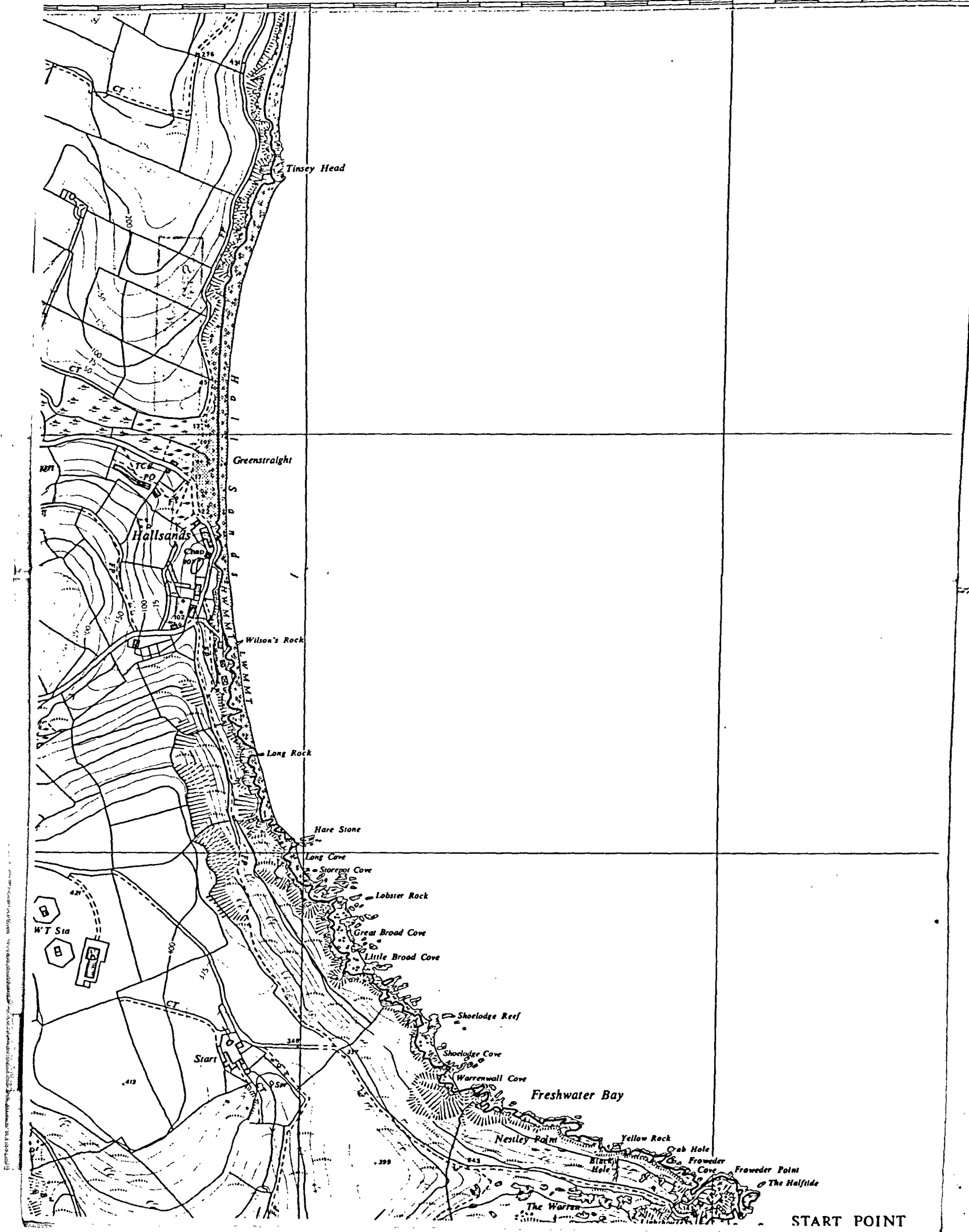


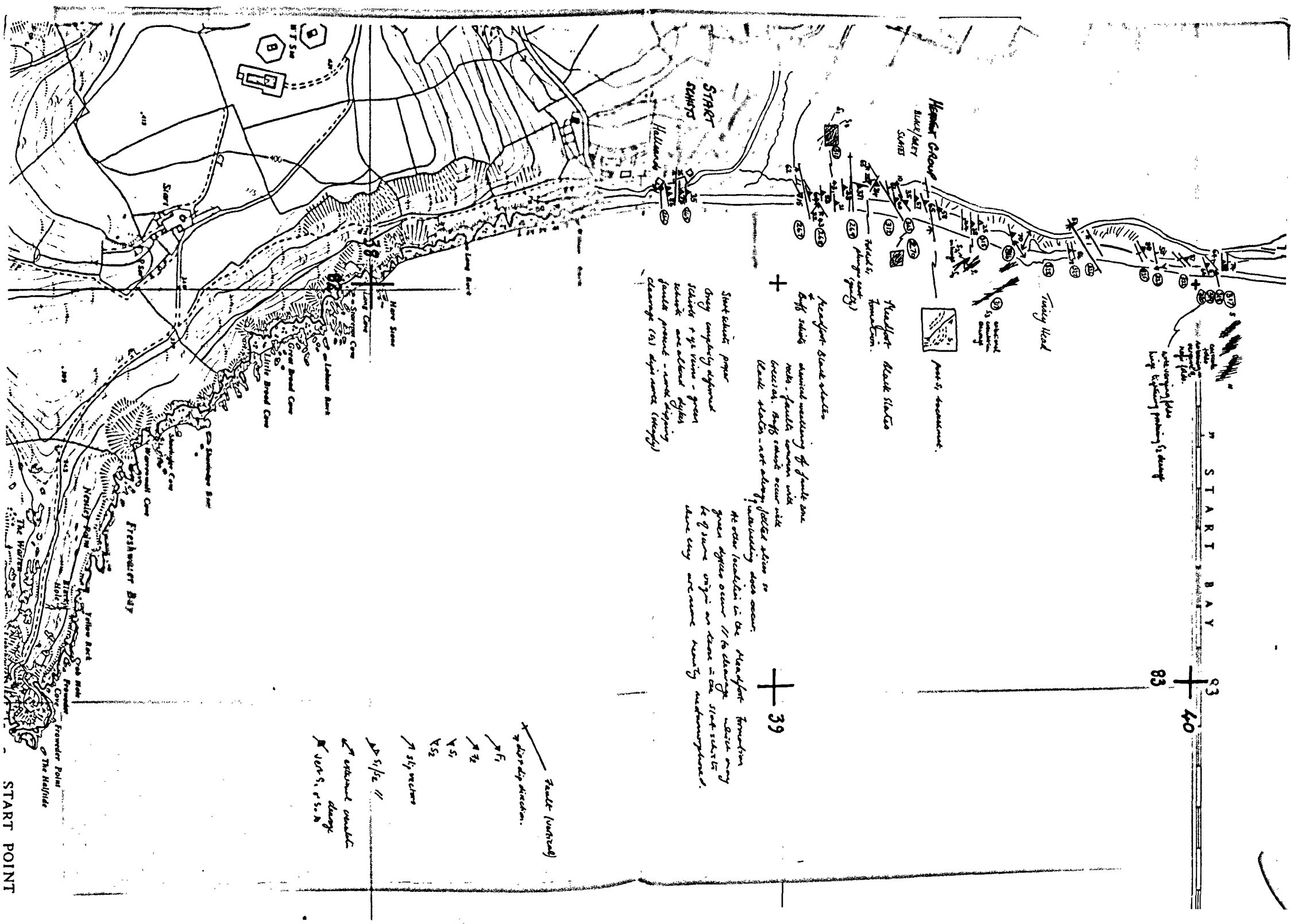
APPENDIX 3

XXXI

POLYTECHNIC SOUTH WEST
LIBRARY SERVICES

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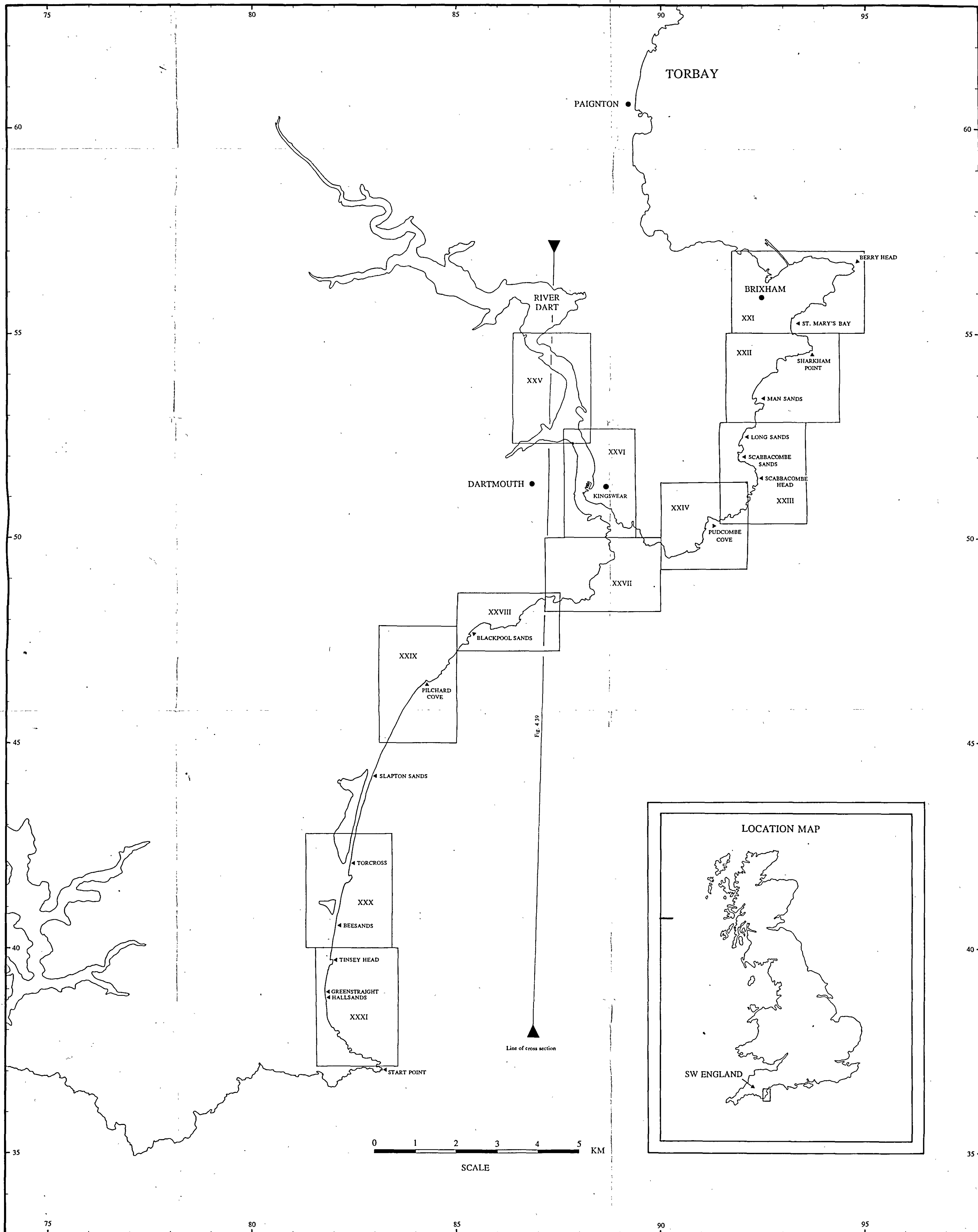


APPENDIX 2

SUMMARY MAP OF THE EAST SOUTH
HAMS COASTLINE
(Torbay to Hallsands)

POLYTECHNIC SOUTH WEST
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APPENDIX 2

SUMMARY MAP OF THE WEST SOUTH
HAMS COASTLINE
(Plymouth to Hope Cove)

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